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# *Scientific Questions for the Exploration of the Terrestrial Planets and Jupiter*

## *A Progress Report of the Advanced Planetary Missions Technology Program*


*R. J. Mackin, Jr.*
*J. B. Adams*
*F. P. Fanale*
*C. B. Farmer*
*L. D. Gray*
*W. S. McDonald*
*E. D. Miner*
*R. L. Newburn*
*G. A. Soffen*



JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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# Preface

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## Abstract

This report is one of a series directed toward providing a scientific basis for priority ordering of experiments for planetary missions in the 1970s. Our approach is evaluation of the potential of experiments and missions for answering questions bearing on the key scientific goals of the planetary program, viz understanding the origin and evolution of the solar system and the distribution and role of life in the solar system. A prior document developed a list of general questions whose answers would give the key to the course of solar system history at crucial points. The present report lists the questions concerning each individual planet which bear upon the more general questions or upon similar questions concerning life. For orientation, the chapter on each planet begins with a resume of the current state of knowledge of that planet. This is followed by a projection of some of the advances in knowledge expected by 1971. Finally, we present the list of questions on the planet, each with remarks on the implications of the question and with a discussion of the types of experiments that will contribute toward answering the question. Several Appendixes treat topics considered worthy of some amplification.

# Introduction and Summary

## I. General Aims

This study is one of a series whose goal is to provide a scientific basis for priority ordering of planetary missions and experiments during the next decade. The approach adopted is to proceed in a sequence of steps from general major goals of solar system science to explicit questions about the individual planets, and then to consideration of experimental techniques for answering these questions. Scientific priorities of the experiments, finally, will be derived by an iterative process that takes into account:

(1) The importance of each question for progress toward general goals.

(2) The possibility of answering or illuminating (shedding some light on) the question by practical techniques.

(3) The power of certain techniques to answer or illuminate a multiplicity of questions.

It is hoped that scientific priorities of various mission types can ultimately be assessed largely by integrating this material in such a way as to display the importance of the advances that each type of mission offers.

## II. Scientific Background

In preparing this report, we have necessarily assumed certain scientific goals that will determine the kind of exploration and, to some extent, the relative priorities of experiments. The two principal goals are: an understanding of the origin and evolution of the solar system, and an understanding of the origin, extent, and role of life in the solar system.

The problem of the origin of the solar system remains largely unsolved. The matter from which the solar system was formed is now widely considered to have existed at some past time as diffuse dust and gas. The initial relation of this matter to the Sun is not known; a currently much discussed hypothesis, however, is that the Sun, and later the planets, accreted from a common reservoir of material. The part of the gas-dust cloud that contracted to form the planets may have been modified both in distribution and chemically by solar radiation. The accretion process itself may have involved a number of stages. Perhaps bodies accreted, broke up, and accreted again. It seems certain that the planetary bodies that were ultimately formed have since been subject to major physical and chemical changes during their histories, largely as a result of internal radioactive heating.

A framework for discussing the major problems that must be solved to understand and reconstruct the origin of the solar system is given in Adams et al. (Ref. 1). These problems are:

(1) Are the individual terrestrial planets and satellites each chemically uniform or nonuniform?

(2) Did final accretion result in the present array and arrangement of planets and satellites, or have these been subsequently altered?

(3) Was the cloud from which the planets condensed chemically homogeneous at the time of final accretion?

(4) What was the state of the Sun–cloud system when it first became a recognizable unit?

(5) Were there large-scale elemental and isotopic nonuniformities in the contracted nebula that was the progenitor of the cloud or the Sun–cloud system?

To the extent that it is possible to answer these questions, it should be possible to reconstruct the chief events and processes in solar system history. Certain kinds of information are needed for each planet in order to achieve these answers.

It seems probable that this information will include data on their motions (orbital and rotatory); on their compositions including the internal state and distribution of mass; on their shape, thermal regime, and surface properties; and on the compositions of their atmospheres.

It would render this report too extensive to attempt a detailed discussion of how such information may relate to the evolution of the solar system and may also be interrelated. For such a discussion, reference may be made to Adams et al. (Ref. 1) and to the list of papers cited by them.

The second scientific goal, that of understanding the origin, extent, and role of life in the solar system, is related in a complex way to the broader questions of solar system evolution. At some time in the evolution of the Earth, conditions became favorable for biogenesis. The environmental conditions necessary for biogenesis are reasonably well known (Ref. 2). These conditions are:

(1) An atmosphere and surface conditions such that liquid water is present.

(2) An atmosphere that is chemically reducing.

(3) Abundance of carbon for carbon chemistry.

But it is not yet clear when in the Earth's history these conditions came to exist and for how long. Furthermore, we do not know whether these conditions ever were reached on other planets. One can consider two periods in a planet's evolution when the environment for biogenesis might exist:

(1) At the effective termination of accretion of the planet.

(2) After self-modification and outgassing of the accreted planet.

It would be of the greatest interest to reconstruct the history of the solar system and of each planet to give a picture of the surface environment at these stages. In practice, the evidence is likely to remain incomplete. Furthermore, past environments have been modified by subsequent external and internal (planetary) processes. Life itself on the Earth has modified the atmosphere and the surface extensively.

The general effect of this modification (often referred to as "biologic feedback") of the Earth's surface and near-surface environment has been to render conditions *less* favorable to subsequent nonbiotic synthesis of high molecular weight organic compounds. An example is the present highly oxidizing atmosphere, which is almost certainly a result of biotic activity and which violates one of the primary requirements listed above for spontaneous synthesis. Thus, the approach required is one of hypothetical "reconstruction" of early terrestrial conditions so as to eliminate such minimal biotic effects on the environment. The "reconstruction" both for the Earth and other planets requires extensive knowledge of present planetary atmospheric compositions – particularly in cases where the absence, or minimal extent, of biotic activity leaves only inorganic modification of the original surface conditions to be accounted for.

The purely biological aspect of the goal, namely that of learning something about the nature of life itself, calls for a direct search for present and/or past life on other planets. In particular we need to know:

(1) Does life exist elsewhere in the solar system?

(2) If it does, is it of different origin from terrestrial life?

(3) If it does not exist elsewhere, why not?

In this study, we have considered (according to the above objectives) the most important data that are needed, evaluated the current and possible near-future knowledge, and investigated the extent to which a modified *Mariner* program could accomplish our scientific goals.

Just as the Adams et al. study (Ref. 1) translated the general goal of understanding the origin and evolution of the solar system into explicit questions about solar system history, a similar study by Fanale and Horowitz (Ref. 2) is directed toward assessing the significance of biology in planetary history along the lines discussed above. When this study is completed it should be possible to provide a broader base for establishing the biological questions for the individual planets.

## III. Contents of the Report

The present report was written in response to urgent requirements of the Advanced Planetary Mission Technology Program for science rationales for a number of planetary missions. Circumstances have prevented its being the actual desired sequel to the general strategy documents, in that it does not trace explicitly the steps from the general questions to the questions for the individual planets. However, it contains much basic material that has been found useful for mission studies and that will provide important elements of the eventual fully derived scientific plan for planetary exploration. For each of the planets, Mercury, Venus, Mars, and Jupiter, it contains:

(1) A discussion of the potential scientific contribution represented by knowledge of that planet.

(2) A succinct summary of pertinent present knowledge.

(3) A projection of foreseeable advances through 1970.

(4) A set of then outstanding questions that bear on the general questions of solar system evolution and on the biological questions of planetary evolution.

(5) For each question, a suggestion of some of the experimental techniques likely to illuminate it ("answer" would probably be too strong a word in nearly all cases, unfortunately). Techniques associated with little-considered 1970-decade missions have been largely omitted.

Expanded discussions of some of the more important questions or areas are given in the Appendixes.

Much of the material presented here has already been incorporated in individual mission studies made during FY 1968.

The missing elements, needed for a complete plan, are:

(1) An explicit derivation of the planetary questions from the general questions.

(2) A consequent assessment of the *importance* of each planetary question, based on how directly or how extensively it is related to the general questions.

(3) Quantitative statements of instrument and mission characteristics necessary for attacking each question.

(4) A retabulation of the question – technique matrix that lists the questions subject to illumination by each technique.

(5) The priority ordering of instrumental techniques (and perhaps mission types) based on a melding of elements (2), (3), and (4).

In connection with element (5), however, it is to be remembered that scientific priority will clearly be only one among several considerations used for experiment selection and mission choice. An ultimate plan should necessarily describe long-range scientific programs for the planets (including astronomical studies) at various levels of support, and should be optimized for various scientific and nonscientific criteria.

Because of the missing elements cited above, as well as the rapid advancement of planetary knowledge, the material herein should be considered as a report on work in progress.

Finally, we note that in the presentation of much immediate and projected scientific information, the authors have perforce been more brief (and thus more arbitrary or dogmatic) than would be appropriate in a strictly scientific account. The chapter on each planet contains references to more complete accounts as well as references that support the assertions in some contentious areas, but extensive referencing has not been included.

## References

1. Adams, J. B., Conel, J. E., Dunne, J. A., Fanale, F., Holstrom, G. B., and Loomis, A. A., "A Strategy for Scientific Exploration of the Terrestrial Planets," to appear in *Rev. Geophys.*, Feb. 1969.

2. Fanale, F., and Horowitz, N. H., "Spontaneous Organic Synthesis and the History of Planetary Volatiles," manuscript in preparation.

# Mars

## I. Present Knowledge

A reasonable accumulation of data about Mars has been acquired, largely from the numerous observations of recent years and from the experiments conducted on the *Mariner IV* mission. However, in almost every area, missing elements of data (or results in which we have little confidence) make our understanding imperfect and our picture of the planet tentative. As an example, the dominant constituent of the atmosphere appears to be $CO_2$, but present data would allow an unknown inert component, such as A or $N_2$, to account for any fraction up to 50%. This uncertainty leads to a basic indefiniteness in any model of the atmosphere's structure or its movements. Another example arises in the conflicting views on the correlation of radar return signals with visible features on the Martian surface. The uncertainty here has so far blocked attempts to relate the markings to plausible topographic features and this, in turn, has been an obstacle to any deeper understanding of the planetary processes reflected by these features. *Mariner* Mars 1969 experiments may resolve the major difficulties in both cases.

The following paragraphs give a succinct account of our knowledge in the areas of Martian planetology, the atmosphere, and the ability to support life.

### A. Bulk Properties and Planetary Interior

The equatorial radius is $3393.4 \pm 4.0$ km from the *Mariner IV* flyby (Ref. 1). The "dynamical flattening" (flattening of the internal mass distribution), derived either from the orbital motion of the satellite Phobos or from the trajectory of *Mariner IV*, is 0.00525. The apparent optical flattening is about two times as large. Spectroscopic studies suggest that this optical flattening does not refer to the solid surface of Mars and, theoretically, it would be difficult to accept, but the effect has not been adequately explained.

The magnetic dipole moment, undetected by *Mariner IV* measurements, is less than $3 \times 10^{-4}$ that of the Earth. In view of the comparable rotation rate, this result suggests that Mars does not possess an appreciable liquid, electrically conducting core. The mean density is 3.94 g-cm$^{-3}$ (intermediate between the Earth and the

Moon). Interior models (density versus radius) designed to reproduce the dynamical flattening do not give a unique answer to the question of a core. Nonetheless, models involving a very small Martian core are the most satisfactory.

However, the relation between this datum and the "degree of differentiation" of Mars is complicated by the second major piece of geophysical data concerning bulk Martian properties; i.e., Mars' low uncompressed density (mean is 3.94 g-cm$^{-3}$). The uncompressed density is roughly intermediate between those of the Earth and the Moon. Besides its obvious implications with regard to the change in the bulk Fe:Si ratio with increasing heliocentric distance, this density also means that Mars would not be expected to have the same dynamic flattening as the Earth even if it were thoroughly differentiated. Much more precise data on the distribution of Mars' mass are needed (presumably from observations of its satellite orbits). Such information would have profound implications for the history of the Martian surface environment.

### B. Physiography

The Martian surface has been seen from Earth with a best resolution of about 100 km; the *Mariner IV* photographs have a best resolution of about 4 km. Earth-based observations show dark areas of irregular shape covering about one-third of the planet, and brighter areas covering the remainder. Polar caps of perhaps water and/or $CO_2$ ice appear seasonally. The bright areas are distinctly orange-colored; the dark areas also reflect a large amount of orange light, but appear brown, gray, green, and blue, visually and in color photographs.

Observations of cloud motions are too rare to have resulted so far in any firm conclusions about Martian atmospheric circulation. Many dark lines traversing the bright areas have reportedly been observed visually, although only the broadest features have been photographed. The existence of the finer features as actual continuous lineaments is in debate.

No agreement exists concerning topographic relations between bright and dark areas. Separate radar observations have given conflicting results as to whether a correlation exists between return signal strength characteristics and surface markings. Strong longitudinal variations in the radar returns, however, indicate that there are large variations in the roughness of Martian topography (Ref. 2).

The critical questions are whether the light and dark areas represent different petrologic provinces like the continents and ocean basins on Earth, and whether topographic differences exist as the result of isostatic compensation for density differences in "continental" and "oceanic" columns.

The surface is covered with craters varying in size from the resolution limit up to at least 120-km diameter. There appear to be more craters on the Martian surface than on the highlands of the Moon. For craters with diameters greater than about 30 km, the size–frequency distribution of craters on Mars is similar to that on the Moon. Below that size, those on Mars are either fewer or statistically less distinct than those of the same size on the Moon.

### C. Surface Materials

The spectral and photometric properties of both the bright and dark areas are consistent with a surface composed primarily of silicates. The reddish coloration and near IR absorption features can be matched by oxidized basaltic rock (Ref. 3). The amount of iron oxide need not be more than a few percent.

The size–frequency distribution of particulate materials is unknown. However, the mean radar cross section (6.3%) is even lower than that of the Moon (7%), suggesting a highly porous surface material (Ref. 2).

### D. Wave of Darkening

The importance of the "wave of darkening" lies in its being a possible clue to the presence of life on Mars. While this interpretation has been challenged, no satisfactory alternative seems to have been put forward. The phenomenon has been described by Sagan and Haughey (Ref. 4) as "a progressive albedo decline of the Martian dark areas (but not the bright areas) starting in local springtime from the edge of the vaporizing polar ice cap, and moving towards and across the equator." There is quantitative evidence that dark areas darken during the Martian spring, reaching maximum darkness after the summer solstice. Whether the darkening occurs as a "wave" from the pole has been contested. A statistical analysis (Ref. 5) showed that, while there are areas that "violate the concept of an invariable wave," there is "a very significant correlation of latitude with the time of maximum darkening."

The waves start alternately from the two polar caps at Martian half-year intervals, cross the equator, and fade at about 22-deg latitude in the opposite hemisphere from which they began. The rate of propagation is variable but averages about 35 km per day. The time from beginning of darkening to maximum darkening is 0.30–0.35 Martian yr in the circumpolar and temperate areas, 0.30 yr at the boundary of the equatorial zone, and 0.15 yr in the equatorial area. The total duration of darkening (minimum to maximum and back to minimum) is 0.67 Martian yr for the wave proceeding from the north cap in the circumpolar areas, and 0.55 yr for the north wave at its southern limit. The wave proceeding from the south cap lasts 0.50 Martian yr in the circumpolar area, and 0.40 yr at its northern limit.

The average darkening of dark areas on Mars increases from poles to equator. The additional darkening resulting from the wave of darkening decreases from poles to equator. This gradient is offset by the effect of the two waves from opposite poles overlapping in the equatorial regions. Additional information on the fine-scale appearance of the various dark areas at different times in the wave cycle is somewhat subjective.

### E. Atmosphere

More than half of the Martian atmosphere is thought to be $CO_2$. Abundance estimates range from 65 to 110 m-atm, with 90 m-atm (6.7 mbar partial pressure) considered a current best value. CO has also been positively identified; its abundance being roughly 10 cm-atm. Spectroscopic evidence has been given for the existence of water vapor in amounts varying from 0 to $30\mu$ precipitable. Results on the total mass of the atmosphere are in some disagreement, but most of the recent values of surface pressure lie between 5 and 15 mbar, with 9 mbar a current best value.

Although ground temperatures may rise as high as 300°K, atmospheric temperatures do not appear to rise as high as 270°K at any time. Calculations indicate that polar air temperatures, even near the surface, may fall to 150°K, the temperature at which $CO_2$ freezes.

The *Mariner IV* experiments found a maximum ionospheric electron density of $9 \pm 1 \times 10^4$ electrons-cm$^{-3}$ and an electron scale height of 22 km on ingress (the day side). The experiments detected no ionosphere ($<4 \times 10^3$ electrons-cm$^{-3}$) on egress (the night side). Numerous model upper atmospheres have been derived from this limited knowledge; the derived exosphere temperatures range from 85 to 550°K for sunspot-minimum flux. If the lower values of the exospheric temperature are valid, it is important to note that the lower Martian exospheric temperature would overcompensate for the lower gravitational field and that, hence, Mars would be more capable than Earth (~1800°K exospheric temperature) of retaining light gaseous constituents.

The Martian atmosphere appears to exhibit two or three types of clouds. White clouds often appear over the polar caps and near various dark areas. They are thought to be condensed vapor, probably of $H_2O$ or $CO_2$.

The Martian atmosphere also seems to contain a general haze that is invisible to the naked eye in unfiltered light, but always photographable in blue or violet light. This "violet layer" or "blue haze" contains irregularities that are often called blue clouds. The exact nature of the general obscuration is unknown. It usually blots out all surface features at wavelengths less than λ4600 in small areas or over most of the visible hemisphere, but the features can be discerned at wavelengths down as far as 4200 Å during "blue clearings."

Yellow clouds are rather rare. They may be very small or, in extremely rare cases, may cover most of a hemisphere. They sometimes persist for days, and may propagate with speeds approaching 150 km/h, although speeds less than 30 km/h are the general rule. The yellow clouds are generally thought to be dust.

### F. Prospects for Presence of Life

The wave of darkening, although not understood, is regarded by some as constituting the strongest present evidence that there may be life on Mars. While there are still unexplained features in the infrared spectra, there is no longer any serious attempt to identify these with organic molecules. The apparent spectral indications of methane or methyl compounds seen in 1965 were not reproduced in 1967.

The spectral indications of water vapor satisfy a supposedly necessary condition for the presence of life, but not a sufficient one. The *Mariner IV* television evidence of a very ancient uneroded surface certainly suggests that abundant liquid water is not present in the area observed. From thermodynamic arguments, liquid water could be present only in local (perhaps even microscopic) regions where a nonequilibrium condition might prevail, but whether unconfined liquid water is necessary for the presence of life is not firmly established.

Rocket measurements of Martian ultraviolet spectra indicate that radiation at wavelengths above 2400 Å reaches the surface in significant quantities. However, even for unprotected living things it would not necessarily be lethal. On Earth, certain life forms can survive in quite intense ionizing radiation fields (e.g., certain algae in nuclear reactor cores).

## II. Expectations Through 1970

### A. Ground-Based Observations

Several major programs of Earth-based investigations of Mars were carried out during the 1967 opposition, and others are planned for 1969. Extremely accurate 21-filter colorimetry was done at Caltech during the past opposition, and the results should be available during 1968. Radiometric mapping was also carried out by Caltech using four channels (9, 11, 13, and 8–14$\mu$), and should result in improved temperature maps, although polar regions were inaccessible. Interferometric spectra taken during 1967 will result in an accurate CO abundance determination, a more accurate surface pressure determination, and improved knowledge of minor atmospheric constituents.

An extended program of reflectance spectroscopy of the polar caps and other parts of the planet during 1969 may settle the question of cap composition. By the end of 1969, photographic spectra should have given improved figures for $CO_2$ and $H_2O$ abundances, distributions, and time variations. Interferometric spectroscopy will be extended to the 2–4$\mu$ region in a new search for minor constituents.

Radar studies of Mars at wavelengths from 3.5 to 70 cm should result in improved knowledge of the gross topography of Mars.

### B. Scientific Expectations of *Mariner* Mars 1969

If successful, the *Mariner* Mars 1969 mission should lead to major advances in our understanding of several unresolved questions about Mars. The following paragraphs indicate the nature of the more likely advances. The mission and its expected results are described in more detail in Appendix A.

*1. Visual imaging.* The best resolution of *Mariner* Mars 1969 TV images will be about 0.1 km, substantially better than that of the best Earth-based photographs of the Moon (about 1 km). They should allow some estimate to be made of, at least, gross surface elevation differences and of cloud heights. Crater statistics will be extended to smaller diameters than seen on *Mariner IV* photographs and will give an indication of the past history of the planet and processes responsible for its surface features. There will be a sufficient number of "canals" photographed to settle their reality or otherwise as surface features, and perhaps their physical character. Far-field photography should give improved accuracy for the visible figure of the planet. With luck, one of the satellites may be photographed, and its size and albedo thus determined.

*2. Infrared radiometer.* The infrared radiometer (IRR) experiment, by mapping the surface temperature, will assist in determining the nature of special features detected in TV images. Examples are light areas, such as were observed around some craters by the *Mariner IV* experiment, and cloud features of various kinds.

By determining the evening temperature decrease, the IRR results should give an improved value for the thermal inertia, which is characteristic of surface texture.

At pressures expected at the Martian surface, $CO_2$ will sublime at 150°K. Through direct measurement of the thermal emission from the southern polar cap, the radiometer experiment will determine whether or not the temperature is low enough to allow $CO_2$ ice formation. This feature of the experiment may be lost if the polar cap has heavy cloud cover during the encounter.

*3. Infrared spectrometer.* The objectives of the infrared spectrometer (IRS) experiment are:

(1) To ascertain the presence of polyatomic molecules.

(2) To determine the compositional variations of atmospheric constituents relative to location on the planet.

(3) To obtain data concerning atmospheric temperature–pressure profiles.

(4) To obtain data concerning surface albedo, temperature, and composition.

The atmospheric composition may lead to important inferences concerning the atmosphere/surface chemical equilibrium.

There is some concern that the low resolution (1%) of the instrument will limit its ability to achieve the first three objectives and that its wavelength range does not include a region where the spectrum is sensibly indicative of surface composition.

*4. Ultraviolet spectrometer.* The ultraviolet spectrometer experiment may reveal the amount and distribution of most of the atomic species in the Martian atmosphere as well as the diatomic species (including some ions) containing C, O, and N. Scale heights of the various constituents, as well as the altitude variation of Rayleigh-scattered light (measured in the twilight just past the terminator), may give a detailed picture of the atmospheric structure over an extended range of altitude. These results will thus strongly complement the occultation experiment. Knowledge of the upper-atmosphere structure will be especially important for determining the basic model that best describes the atmosphere, and for indicating the possible role of the solar wind in the evolution of the atmosphere. Repeated measurements ultimately will be needed to determine the seasonal and solar-cycle effects, which are expected to be large.*

The possible features of the data might include $O_3$ absorption, effects of clouds, and night air glow.

*5. S-band occultation.* This experiment will provide for separate Martian surface pressure and altitude profile measurements, thus refining the conclusions of the *Mariner* Mars 1964 experiment. The experiment will be greatly assisted by the composition measurements, which will restrict the range of models that can be used in its interpretation.

It will be of particular interest, for theoretical models of charged-particle effects, to compare ionospheric densities with those measured on the *Mariner IV* mission near the sunspot minimum.

It seems unlikely that *Mariner* Mars 1969 will shed appreciable light on the wave of darkening or on the explicit question of the presence of life on Mars.

### C. Expectations From U.S.S.R. Missions

It is widely expected, on the basis of past history, that the U.S.S.R. will attempt to land a capsule on Mars in 1969. The atmospheric entry accomplished at Venus suggests that they have a good chance of succeeding in their effort. With their present limited telemetry capability, it seems plausible that their measurements will be comparable with those performed on Venus: temperature, pressure, and density profiles of the atmosphere, and some gross atmospheric measurements. However, the sensitivity of the water vapor detector would have to be about three orders of magnitude better than that of the one used on Venus, if the abundance is something like the average indicated by the spectroscopic measurements.

It would not be unreasonable to expect a Soviet Mars Orbiter in 1969, based on their lunar orbiter capability. This mission might produce the first significant measurements of spatial variations in atmospheric constituents or parameters, as well as an idea of surface composition from gamma-ray measurements. It would be reasonable to expect them to make more detailed measurements of the magnetic environment than those of the *Mariner IV* flyby.

In view of our inability to gauge the probability of Russian experimental accomplishments in 1969, we merely note them but do not delete from the question list those points that they might answer.

*J. Gunn, 1968 (private communication).

## III. Questions to be Answered by Future Space Experiments

The questions (and associated suggested measurement techniques) are listed by category: planetology, atmosphere and clouds, biology, and wave of darkening. The last, rather narrow category may be thought of as an amplified question in the biology set determining whether the wave of darkening is a result of the presence of life. The phenomenon is of dramatic importance if it is a biological one (since its detection from Earth would imply the presence of dense or massive growths), but apparently only a moderately interesting enigma if it is not life-related. The attention given it herein reflects in part the fact that the 1971 opportunity is especially well timed for observations to be made on the wave of darkening.

The treatment herein of biology questions is comparatively cursory. A detailed strategy for an attack on the life-detection problem was published internally by JPL.* Although the document was written in the context of *Voyager* class missions, many of the main scientific ideas are applicable to smaller landers.

### A. Planetology

(1) *What is the internal mass distribution?* The internal mass distribution must be derived from measurements of the visible shape of the planet (see question 2), the mean density, and the ratio of the moments of inertia. The last can, in principle, be

*"The Biological Exploration of Mars – A Plan for the First Three Missions," edited by H. Ford, Aug. 15, 1967.

derived from the precise tracking of an orbiter in a substantially inclined orbit.

As to whether Mars has a core or if it is liquid, the absence of a magnetic field and the low uncompressed density suggest that a core is very small or absent or solid. Direct information on a core probably requires an array of landed seismic measurements. However, if the asymmetry (see question 2) is markedly incompatible with that of a rotating fluid of the appropriate density, central stresses will be implied which are inconsistent with the presence of a liquid core; that is, the center of the planet would be a rigid structure supporting asymmetric forces. (A small inconsistency could be explained by noncentral body stresses such as apparently exist in the Earth's mantle.)

(2) *What is the shape of the planet?* Far-field pictures (*Mariner* Mars 1969) will give the shape but may be subject to systematic errors because of the atmosphere and phase effects. Orbital (i.e., repeated) radio occultation measurements will give the shape and will not be subject to this possible error. Integration of orbital topographic measurements (including radar; see question 5) will give further information on the shape.

(3) *What are the thermal regime and its history, the sources of heat, and the seismic activity?* Evidence will be provided by synoptic thermal mapping with an IR radiometer from orbit. The experiment requires a highly inclined orbit. Further data will be required from landed subsurface heat flow measurements, landed seismometers, and inferences on past heat flow from compiled geologic data.

(4) *What is the composition of the surface (including radioactive nuclides) and its petrologic nature?* Indicative data can be obtained from orbit by a gamma-ray spectrometer, near-IR low-resolution spectrometer, or (less explicit) radar. Pertinent landed instruments include an alpha-scattering instrument (plus X-ray fluorescence detector, preferably), a permanent magnet (requires imaging), an X-ray diffractometer (plus DTA, preferably), and a petrographic microscope. The last two require sample acquisition. A landed gamma-ray spectrometer will detect nuclides emitting low-energy radiation. Landed imagery will indicate rock forms, granularity of soil, and other surface features.

(5) *What is the nature of the topography, the surface expression of interior processes?* The following orbital experiments are pertinent: optical imagery, utilizing shadow and stereo effects to indicate slopes and elevations (to tens of meters); repeated Earth-occultation to give systematics of maximum elevations; and imaging radar. A high-resolution IR spectrometer can give elevations to 1 km based on range in $CO_2$ (Ref. 6). Any of these observations, if made in sufficient quantity, can probably be used to derive the figure of the planet. Landed imaging will give a sample of fine scale topography. A landed gravimeter will give the elevation at the landing point.

(6) *What are the densities and surface compositions of the satellites?* With a fortuitous encounter, orbital imagery could give size, shape, and perhaps surface detail; orbital tracking, if the encounter is still closer, could give the mass. A low-resolution near-IR spectrometer may give information on surface composition.

(7) *What is the composition of the polar caps?* (See following question 3 under atmosphere.)

## B. Atmosphere

(1) *What is the detailed composition of the atmosphere?* Of particular interest are the concentrations of the inert atmospheric elements (A, Ne) and their isotopic species. Data for the upper atmosphere can be obtained by a filtered radiometer in the entry system for shock wave analysis, and for the lower atmosphere by flyby or orbital UV spectroscopy and high-resolution IR spectroscopy, entry or landed mass spectrometer, gas chromatograph, and water vapor detector. UV spectroscopy generally detects emission lines from atoms and absorption lines from diatomic molecules, including ions and free radicals. At least some radiation between 2000 and 3000 Å apparently penetrates to the surface. IR spectroscopy generally detects absorption lines from diatomic and polyatomic molecules. Trace constituents may require resolution of the order of 0.5 $cm^{-1}$ for detection. For some applications, it may be preferable to replace measurements on reflected light with measurements on solar radiation transmitted through the atmosphere.

(2) *What is the origin of the constituent gases?* Entry or landed mass spectrometry will give isotope

ratios from which may be deduced the origin of inert elements with implications for the origin and history of Martian volatiles in general. If it detects trace constituents that represent a departure from a known steady-state equilibrium, they could possibly indicate a biological origin (see question 5 under biology).

(3) *What is the composition of the polar caps; in particular, what are their trace constituents that may have biological or planetological significance?* Ground-based IR spectra supplemented by appropriate laboratory studies may indicate the major components. Orbital high-resolution IR spectroscopy may indicate selected vapor concentrations over melting poles. Landed composition measurements on a polar cap (e.g., by alpha-scattering instrument) will be required for determination of trace components.

(4) *What are the pressure and temperature characteristics of the atmosphere; i.e., how do the altitude profiles vary with latitude, with time of day, and with season?* UV spectroscopy of Rayleigh-scattered radiation in the twilight layer gives the density profile there; radio occultation (given the composition) gives density profiles in other zones; and high-resolution IR spectrometry, in principle, gives density and temperature profiles along scan path. Thus, orbital UV spectroscopy (twilight) gives latitude and seasonal effect at twilight; orbital occultation gives broad distribution of density profiles; and orbital high-resolution IR spectrometer gives all desired information on the dayside. An entering aerometry experiment gives the density profile at one location, but explicitly; it would thus serve as a good calibration of remote sensing techniques. Landed meteorological measurements give diurnal variation of pressure and temperature at surface, serving as a valuable explicit end point. Probably only the landed measurements and the occultation will give nighttime values of these quantities.

(5) *What are the nature and properties of the colored hazes and the clouds?* The following orbital techniques appear useful. Imagery will give cloud height, where clouds and their shadows can be seen. High-resolution IR spectrometry will give cloud-top elevations to 1 km based on range in $CO_2$. Orbital plus ground-based imagery will give systematics of cloud formation, growth, and disappearance; filtered imagery will do the same for hazes. An IR spectrometer may give composition, temperature, and particle size when theoretical techniques for interpretation of data are somewhat more advanced. Orbital UV spectroscopy may give the haze composition. A mass spectrometer on an entry probe (if it passes through thick enough haze) will give direct composition measurements. Imagery, by correlation of cloud formation with certain locations, may indicate the sources of clouds. Correlated orbital and ground-based imagery could indicate movements of clouds, and thus give wind speeds at known altitudes.

(6) *What is the nature of the general circulation of the atmosphere?* Orbital cloud movement studies (see previous question 5) may indicate certain wind patterns. Orbital multichannel high-resolution IR spectroscopy will give pressure and temperature profile maps for use in a model. Landed wind measurements will both give an important end point and indicate the presence or absence of a very thick surface boundary layer.

### C. Biology

The following questions are related to the environment for life or indications of life.

(1) *Are there any living organisms?* Landed life detection experiments seem essential. Based on Earth analogy, these experiments require, in general, several days of operation for meaningful results (except for imagery and chemical analysis).

(2) *Is organic material present in the soil and what is its nature?* A landed pyrolysis experiment with gas-chromatograph/mass-spectrometer analysis of effluent gases is appropriate.

(3) *What are the best landing sites for future missions: interesting features, and locations of significant visible change, color, local moisture accumulations, and nonhazardous topography?* Orbital imaging, thermal mapping by IR radiometer, and water mapping (by techniques cited under question 4) will all contribute.

(4) *Is water present and, if so, what is its distribution?* The following three forms of water must be considered:

(a) Permafrost and its manifestations. Landed electro-magnetic techniques (perhaps ambiguous), landed subsurface sample analysis (including, at least, differential thermal analysis), and landed imagery for patterned ground are all appropriate. Orbital radar is a marginal possibility.

(b) Local vapor concentrations. Orbital water vapor mapping by high-resolution IR spectroscopy, or microwave radiometer seems feasible.

(c) Liquid water. Orbital, visible, or radar imaging or passive microwave measurements could detect sufficiently large bodies of water.

(5) *What atmospheric trace constituents are present and how are they distributed?* (These may indicate a concentration of substances related to life, history of metabolic activity, e.g., $N_2$ and $O_2$, or a departure from thermodynamic equilibrium.) The measurement techniques are covered under question 1 in the previous atmosphere subsection.

(6) *What is the diurnal variation of selected atmospheric constituents?* These data may give indirect evidence of metabolic activity. A landed gas chromatograph with at least 1-day operation time is a simple approach. Orbital IR or UV spectroscopy in some cases give dayside coverage.

(7) *What are the photochemical reaction products (e.g., ions, free radicals, and stable molecules)?* These may aid in interpretation of composition analysis or be indicative of surface environment. An orbital UV spectrometer should detect many of them.

(8) *What is the nature of the mineralogy?* Examples of mineralogical constituents and properties of biological interest are:

(a) Soluble ions, which may have metabolic role. Landed conductivity measurements with sample will indicate presence of these.

(b) Water of hydration, presence and release characteristics. This can be studied by a landed differential thermal analysis (DTA) plus $H_2O$ detector, or by wide-line nuclear magnetic resonance (NMR). Both techniques require sample acquisition.

(c) Ability of surface material to fix nitrogen or oxygen. Landed detailed chemical analysis (alpha-scattering instrument plus DTA plus gas chromatograph or X-ray diffractometer) should give strong clues to this.

(d) Unique micro-environment (e.g., small cracks, capillaries). Landed low-power microscopy may be required to search for such micro-environments.

### D. Wave of Darkening

(1) *Does the wave of darkening have a biological origin?* Is the wave due to an increase in material containing organic compounds? Techniques include orbital IR spectroscopy in the 3–4$\mu$ range, and landed chemical or fluorescence analysis. The latter requires a comparison of "darkened" and "undarkened" areas; therefore, either measurements must be made at two sites or a landing achieved just ahead of the wave and measurements conducted throughout the interval of "darkening."

Does the wave of darkening represent textural or structural development? Orbital high-resolution imagery may indicate or at least suggest this effect. Landed imagery is best, but requires comparison of darkened and nondarkened areas as described above.

(2) *Does the wave of darkening represent a change in chemical composition or crystalline form, or a mechanical movement of surface material?* Orbital IR spectroscopy may give indications. Landed imagery and chemical analysis at a selected latitude and a duration of several weeks, or intercomparison of similar darkened and nondarkened areas are stronger possibilities.

(3) *Is the wave of darkening correlated with the general wind circulation?* Video mapping (correlation of wave of darkening with cloud formation and movement) and landed wind measurements will directly contribute. Temperature mapping and sounding will support circulation models.

(4) *Is there a systematic connection between the wave of darkening and topography?* Orbital imagery and possibly radar can be directed toward this question. Perhaps correlations with IR radiometer (surface temperature) data will be indicative.

(5) *Is the wave of darkening correlated with local atmospheric composition, especially water vapor?* Techniques include orbital high-resolution IR spectroscopy ($H_2O$ absorption bands) or microwave radiometry, and landed atmospheric composition analysis (mass spectrometer, gas chromatograph,

and water-vapor detector). The experiment requires comparison of darkened and nondarkened areas.

(6) *In what way is the development and decay of the polar caps directly connected with the wave of darkening?* General meteorological measurements will make suggestive contributions toward proposal and evaluation of models. The answer to this question will probably follow rather than precede the discovery of the nature of the wave of darkening.

## References

1. Cain, D. L., "The Implications of a New Mars Mass and Radius," in *Supporting Research and Advanced Development*, Space Programs Summary 37-43, Vol. IV, p. 7. Jet Propulsion Laboratory, Pasadena, Calif., Feb. 28, 1967.

2. Carpenter, R. L., "1967 Radar Observation of Mars," in *Supporting Research and Advanced Development*, Space Programs Summary 37-48, Vol. III, p. 157. Jet Propulsion Laboratory, Pasadena, Calif., Dec. 31, 1967.

3. Adams, J. B., "Lunar and Martian Surfaces: Petrologic Significance of Absorption Bands in the Near-Infrared," *Science*, Vol. 159, pp. 1453–1455, 1968.

4. Sagan, C., and Haughey, J. W., "Launch Opportunities and Seasonal Activity on Mars," in *Biology and the Exploration of Mars*, pp. 283–291. Edited by C. S. Pittendrigh, W. Vishniac, and J. P. Pearman. National Academy of Sciences – National Research Council, Washington, D.C., 1966.

5. Pollack, J. B., Greenberg, E. H., and Sagan, C., "A Statistical Analysis of the Martian Wave of Darkening and Related Phenomena," *Planetary Space Sci.*, Vol. 15, pp. 817–824, 1967.

6. McClatchey, R., "An Experiment for the Determination of Martian Surface and Cloud-Top Elevations," in *Supporting Research and Advanced Development*, Space Programs Summary 37-44, Vol. IV, p. 217. Jet Propulsion Laboratory, Pasadena, Calif., Apr. 30, 1967.

## General Reference

Michaux, C. M., *Handbook of the Physical Properties of the Planet Mars*, NASA SP-3030. National Aeronautics and Space Administration, Washington, D.C., 1967.

# Venus

## I. Scientific Importance

The well-known clouds of Venus prevent any optical observations of its surface. In the past ten years, the non-visible surface has been studied by radar and passive radio astronomy with two remarkable results.

First, the surface is much hotter ($\gtrsim$600°K) than was believed possible on the basis of a simple radiation energy balance. For radiative equilibrium, the atmospheric temperature should be ~235°K, and the surface temperature was not expected to be very much higher than that of the atmosphere.

Second, the axial rotation is retrograde and extremely slow. Not only is its rotation the slowest in the solar system, but it appears to be locked to the orbital motion of the Earth, so that the same side of Venus faces us each time it comes to inferior conjunction. Recent observations of Venus have shown that the atmospheric pressure at the surface is 20–130 times that on Earth, that the atmosphere is composed mostly of carbon dioxide, and that traces of highly reactive gases (HCl and HF) are present in the atmosphere.

It is surprising that this planet, which is the most similar to the Earth in size, mass, and distance from the Sun, should be so very unlike the Earth in many respects. The most puzzling question is the apparent comparative scarcity of water – whose inventory on Earth is twenty times as great as that of $CO_2$ (free plus bound as carbonate). To determine the evolutionary processes that have caused Venus to be so different, more information about the present condition on Venus must be obtained. Such basic data as the atmospheric composition, surface temperature, and pressure are only approximately known. The nature of the clouds, surface features, and the principal moments of inertia of the planet remain unknown. Many questions have to be answered before an attempt can be made with confidence to test any theory of the origin and evolution of Venus.

## II. Present Knowledge of Venus

Venus is slightly smaller and less massive than Earth. Radar observations have given the radius of the reflecting layer (presumably the solid surface) as 6056 km. The mass is about 0.815 that of the Earth's mass and is known with high accuracy from the orbits of *Mariner II* and *Mariner V*. This mass, together with the radar value for the radius, gives a mean density of 5.23 g-cm$^{-3}$. Radar observations have given the axial rotation period as 243.1 ± 0.1 days, with the direction of rotation retrograde. Thus, the length of the solar day on Venus is about 117 terrestrial days. The size and shape of the orbit are known with high precision, partly as a result of radar observations. In fact, radar observations of Venus have calibrated the linear scale of the solar system so accurately that the greater part of the remaining uncertainty arises from the error in the measurement of the speed of light.

The nature of the main body of the planet (its interior, surface, topography, and petrology) remains unknown. The rotation period appears to be a synodic resonance period, as already mentioned, which may require dissipative mechanisms in a liquid core for its establishment. *Mariner V* measurements have set an upper limit to the Venus magnetic field of $2 \times 10^{-3}$ that of the Earth; however, the implications of this result regarding the presence of a liquid core are unclear in view of the present uncertainties about the dynamo-theory explanation of the Earth's field. If the constitution of Venus is similar to that of the Earth, then a radius as small as 6056 km would require a liquid core comprising 20% of the entire mass. Moreover, the existence of a liquid core may imply mountain building at the surface (Ref. 1); accordingly, a search for evidence of such topography could be of great theoretical value.

Ground-based radar observations have indicated a number of extensive features on the surface of the planet which give especially strong return signals cross-polarized with respect to the incident signals. These features have been interpreted as areas of high surface roughness, but nothing is known about their relative elevations. The reflectivity of Venus at 12.5 cm has been found to be 0.11, reasonably constant over a 90-deg range of planetocentric longitude. This reflectivity corresponds to an average dielectric constant of approximately 4.

The atmosphere is about 90% carbon dioxide, and the composition of the remainder is largely unknown. Argon, neon, and nitrogen have been suggested. The Russian probe *Venus 4* found 0.4–0.8% of $O_2$ (more than a factor of 10 over the upper limit indicated spectroscopically) and estimated 0.1–0.7% of $H_2O$ present in the lower atmosphere. An upper limit of 7% was set for $N_2$. This experiment is the only direct (or *in situ*) measurement of atmospheric composition, and these results should certainly be checked. The $N_2$/Ne ratio, the Ar content, and isotopic composition are still not known. These are prerequisite for any confident projection of Venus' atmospheric evolution.

The surface pressure reported by *Venus 4* was 20 ± 2 atm; the near-surface temperature, measured by *Venus 4* at a point near the equator and 1500 km from the terminator on the dark side, was 543 ± 7°K. This temperature is somewhat lower than that inferred from centimeter-wavelength radio and radar data (600–700°K). Unfortunately, a 24–30-km discrepancy between the Venus radius inferred from the *Venus 4* data and that from the ground-based radar and supporting data creates concern that the *Venus 4* altitude measurement may have been in error by this amount. If so, then the surface pressure appears to be some 130 atm and the temperature 700°K. Radio data indicate that the surface temperature is rather uniform over the planet, but spatial differences as large as 100°K or so are still possible.

The optical properties of the obscuring clouds enter into the interpretation of most spectroscopic observations of Venus. Uncertainties in the cloud properties and in the basic theory itself cause inferences from these data to be uncertain by a factor of 2 or more. The effective pressure for the formation of spectral lines observed in the near infrared is on the order of 0.1 atm (0.04–0.2 atm) and the corresponding temperature is about 240°K. This temperature is in agreement with the radiometric cloud temperature (~235°K) measured at 10$\mu$. Some minor constituents have been identified spectroscopically: CO (45 ppm), HCl (0.6 ppm), and HF (0.005 ppm). Ground-based spectroscopic observations indicate that the total water-vapor content above the clouds varies from zero to tens of microns precipitable water. Since the *Mariner V* data indicate a constant stratospheric temperature of about 235°K, there does not appear to be enough water vapor to be in equilibrium with either ice or water droplet clouds.

The height of the cloud tops is not known, but it is probably close to the tropopause height of 30–50 km above the surface. The state of the lower atmosphere appears to be close to adiabatic equilibrium, with a constant lapse rate of 9.7°K/km. This indicates that the lower atmosphere of Venus is probably in convective equilibrium, like the atmosphere of Earth. Unfortunately, nothing is known about the general atmospheric circulation. Ultraviolet photographs show cloud features whose variations, if interpreted as circulatory motions, suggest a circumpolar circulation period of about 4–5 days, corresponding to wind speeds of 300 km/h. On the other hand, the reported kinematics of the *Venus 4* parachute descent are consistent with gentle gas motion below the tropopause. The neutral atmosphere was first observed at 90-km altitude (relative to a surface at 6056 km) where the pressure is about 0.001 atm. The scale height of the atmosphere at 60–70 km is about 5.4 km.

The upper atmosphere apparently contains about $10^{-3}$ as much neutral atomic hydrogen as does the Earth's upper atmosphere. The experimental upper limit for the quantity of atomic oxygen above the 200-km level is $10^{-5}$–$10^{-8}$ times less than the amount at corresponding heights in the Earth's atmosphere. The ionospheric electron density above the 100-km level is about $10^{3}/cm^{3}$ on the dark side of Venus and $10^{5}$–$10^{6}$ $cm^{-3}$ on the sunlit hemisphere.

*Mariner V* results showed the interaction of the solar wind with Venus to be different from the solar-wind interaction with either the Earth or Moon. The upper boundary of the daylight ionosphere appears to be very close to the planet (about 500 km altitude).

## III. The Immediate Future: What is Expected to be Known by 1970

Improvements in imaging radar resolution should result in better indications of the topography of the planet. A near-future resolution of 30 km seems feasible, but only over restricted portions of the disk. The fact that Venus presents the same face to Earth at every opposition will make most areas "visible" only from greater distances, with corresponding lower resolution. Perhaps improved radar measurements could also give a direct measure of large-scale surface irregularities, such as mountain ranges.

Thermal mapping of Venus at 3-cm wavelength has already begun, so that approximate thermal distributions should be available by 1969. The opacity of the atmosphere is higher at 3 cm than at longer wavelengths; thus the thermal maps should relate primarily to the lower atmosphere.

The controversy regarding the presence, amount, and variability of atmospheric water should be resolved by further spectroscopic measurements in the photographic, infrared, and millimeter wave regions. Observations should be made with both ground-based and balloon or aircraft platforms. High-resolution infrared spectra may be obtained in the 2.5–4$\mu$ region, and these spectra could give some indirect indication of the cloud properties from changes in the spectral albedo. Low-resolution spectra have shown a large change of the albedo in this region. It will be interesting to see if the effective temperature for spectral line formation is the same at 3–4$\mu$ as the 235°K found for lines near 1$\mu$ and for the clouds at 10$\mu$. The possibility also exists that unexpected molecular species will be discovered to be present in the Venus atmosphere.

## IV. Questions to be Answered by Future Space Experiments

Although recent advances represent a large step forward in our knowledge of Venus and appear to tie together several classes of data (e.g., the radio absorption at centimeter wavelengths and the pressure profile and gross composition), the list of unanswered significant questions is still a long one. The following paragraphs contain the questions together with some suggested techniques for answering them. Planetological questions will be dealt with only briefly, since the techniques for giving significant answers to most of them involve landers, which are still not included in the NASA program. The special scientific importance of the clouds is emphasized in Appendix B and the isotopic composition of inert atmospheric elements in Appendix C. Appendix D gives detailed attention to the problems of the determination of the water content of the atmosphere. The intriguing speculative question of possible life on Venus is omitted "without prejudice."

### A. Planetology

(1) *What is the internal mass distribution?* A check on the internal mass distribution could be derived from measurements of the radar image of the planet shape (see following question 2), the mean density, and the moments of inertia. The ratios of the moments of inertia can be determined from the precise tracking of an orbiter in an orbit substantially inclined with respect to the symmetry axis.

Direct information on a core probably requires an array of landed seismic measurements.

(2) *What is the shape of the planet?* Orbiting radar altimetry will describe the shape if adequate areal coverage is obtained. Integration of orbital radar topographic measurements will give further information.

(3) *What are the thermal regime, its history, and the sources of heat; and are there volcanoes and seismic activity?* Thermal mapping with a microwave radiometer from a highly inclined orbit (to give overall coverage) will indicate the general thermal regime. Landed subsurface heat flow measurements and a landed seismometer will be

required for a clear indication of interior processes. Volcanic activity may be inferred if characteristic products are found in the clouds or atmosphere.

(4) *What is the composition of the surface (including radioactive nuclides) and its petrologic nature?* Orbital radar plus a microwave radiometer offer the promise of a coarse emissivity map indicative of composition and its variations. However, landed instruments will be required for definitive measurements. The alpha-scattering instrument (plus X-ray fluorescence detector, preferably) and the X-ray diffractometer (plus DTA, preferably) are choice tools for mineralogical analysis. Each of these instruments will require acquisition of a sample and evacuation of the test chamber into which it is placed. Landed imagery (probably using artificial light) will indicate rock forms, granularity of soil, and other petrographic features.

(5) *What is the nature of the topography, the surface expression of the planetary processes: especially are there mountain ranges of terrestrial type?* Topography to a resolution of tens of meters can be determined by orbital radar imagery utilizing signal strength and stereo effects to indicate slopes and elevations (with the latter confirmed by radar altimetry). Associated passive microwave measurements will be required for unambiguous interpretation. Landed imaging would give a sample of fine-scale topography. A landed gravimeter (or ranging transponder) would give the elevation at the landing point.

## B. Atmosphere and Clouds

(1) *What is the composition of the atmosphere?*

(a) Are the minor constituents uniformly mixed throughout the atmosphere?

(b) Can any constituents condense to form liquids on the surface of the planet?

(c) Are the atmosphere and surface in equilibrium?

(d) Are argon, neon, or nitrogen present in the atmosphere, and what is their origin?

(e) How is the abundance of these gases related to that of the major constituent $CO_2$?

(f) What ionic species are present in the upper atmosphere?

(g) What is the photochemistry of the upper atmosphere?

Composition of the upper atmosphere may be determined in part by flyby or orbiting UV spectroscopy. A filtered radiometer for shock-wave analysis on an entering vehicle may give composition information at the elevation of maximum deceleration. High-resolution IR spectroscopy can analyze much of the region above the clouds; in and below the clouds requires a descending or landed mass-spectrometer, gas chromatograph, and water-vapor detector. For some of the spectroscopic applications, it may be preferable to replace measurements on reflected light by measurements of solar radiation transmitted through the atmosphere. Microwave radiometry in selected bands may be able to indicate the altitude distribution of certain components (e.g., water). The surface measurements cited under Section IV-A (planetology) may indicate the presence of liquids.

An entering composition experiment would only give a profile at one location, but explicitly; thus it would serve as a good calibration of remote sensing techniques. For proper interpretation, it would necessarily be supplemented by aerometric measurements ($p$, $T$, $\rho$) on the same vehicle.

Some ionic species in the upper atmosphere may be detected spectrally; others will require an ion mass spectrometer on an entering vehicle.

A Venus balloon system capable of moving up and down over a substantial altitude range, and expected possibly to be blown over a substantial range of the planet surface, will be a powerful tool for any of the desired profile measurements, such as composition.

Entry or landed mass spectrometry will give isotope ratios from which may be deduced the origin of inert elements.

(2) *What is the distribution and chemical composition of the clouds?*

(a) Are the clouds composed of condensed vapors or of solid particles?

(b) If the cloud particles are solids, are they ice crystals (or other condensables) or dust?

(c) If the clouds are dust, is the dust the result of volcanic eruption or of surface disintegration?

(d) What size are the particles?

(e) Are the clouds uniformly distributed vertically in the atmosphere, or are there several cloud layers?

(f) Are the dark features of the clouds, seen in the ultraviolet, higher or lower in the atmosphere than the light features?

Cloud composition measurements, in the absence of spectroscopic breakthroughs, will probably require *in situ* experiments that involve collecting samples, processing (e.g., heating), and analyzing them by mass spectrometer or gas chromatograph.

A calorimetric experiment to search for the melting and boiling points of particles could be used to distinguish between water, organic materials, and silicate materials.

The balloon system cited above will be most valuable if it can be made to reach cloud altitudes, both to conduct systematic extended samplings of cloud material and to study the wind patterns there.

Transmittance of sunlight may give a figure for mean particle size, but not for size distribution. Orbital imagery in the visible and near-UV regions of the spectrum may be the most powerful technique for determining the type, distribution, and movement of the clouds.

(3) *What is the general circulation pattern of the atmosphere?*

(a) Is there any variation of the vertical temperature or compositional profiles with latitude?

(b) Are the polar regions cooler than the equatorial region?

(c) Is the high surface temperature due to a greenhouse effect, to convective heating, or to what effect?

(d) To what extent is the atmosphere responsible for a redistribution of surface or internal material?

(e) Why is there so little variation in temperature between the dayside and the nightside?

(f) Are there high-speed winds on Venus?

Radiometric measurements of the extinction of sunlight in the cloud layer, together with spectral measurements of the infrared radiance of the lower atmosphere, should provide adequate information for answering most of the outstanding atmospheric model questions. Accelerometers (and probably an altimeter) on an entry vehicle during parachute descent phase will give a sample of the wind profile. More systematic measurements could be made by balloon-borne instrumentation, and landed meteorological measurements will be a desirable adjunct. Landed imagery could indicate the existence of significant dust storms or other physical atmosphere–surface interactions. Simpler devices would be sufficient to indicate the accumulation of dust on a landed capsule, however.

## Reference

1. Lyttleton, R. A., *On the Internal Constitution of the Terrestrial Planets*, Technical Report 32-522. Jet Propulsion Laboratory, Pasadena, Calif., 1963.

## General References

Jastrow, R., "The Planet Venus," *Science*, Vol. 160, 1968.

Koenig, L. R., Murray, F. W., Michaux, C. M., and Hyatt, H. A., *Handbook of the Physical Properties of the Planet Venus*, NASA SP-3029. National Aeronautics and Space Administration, Washington, D.C., 1967.

# Mercury

## I. Introduction

Several factors have recently caused an upsurge of interest in the planet Mercury, which until now has received relatively little attention from planetary scientists. Mercury may constitute an "end point" for testing any theory of solar system origin. Its high density could well imply a bulk chemical composition different from most of the terrestrial planets. The discovery that its rotation is not synchronous (1 yr = 1 sidereal day) but resonant (in the mode, 2 yr = 3 sidereal days = 1 solar day) has given rise to reconsideration of its interior properties in the course of theoretical attempts to explain the resonant rotation. Finally, the recent discovery that, in 1970 and 1973, it is more easily accessible to a space vehicle than previously supposed (by means of a close Venus flyby that uses the deflection imparted by the Venus gravity field to achieve the desired trajectory) has now made a Mercury space mission appear feasible in the immediate future.

The 1973 opportunity is chosen as the earliest for which it appears that a mission might be funded. More important, 1973 (and possibly 1975) offer probably the only opportunities relevant to this report, inasmuch as the relative positions of Earth, Venus, and Mercury will not permit another Venus swing-by opportunity until 1991.

This chapter presents discussions of the present knowledge of Mercury, the prospects for new information on Mercury prior to 1973, scientific questions about Mercury that have a bearing on the larger questions (see Introduction chapter) concerning the evolution of the solar system, and some of the experimental techniques for attempting to answer them.

## II. Present Knowledge

This section contains a summary of the more pertinent facts about Mercury. References are given only where some discussion of them is required. Most of the recent information has appeared in the *Astrophysical Journal* and the *Astronomical Journal*, or in references cited in these journals.

### A. Orbital Parameters and Body Properties

The following values are current as of January 1968:

| *Item* | *Value* |
|---|---|
| Perihelion | $46.0 \times 10^{6}$ km |
| Aphelion | $69.8 \times 10^{6}$ km |
| Orbital period | 88.21 sidereal days |
| Radius | $2434 \pm 2$ km |
| Mass | $0.330 (\pm 0.003) \times 10^{27}$ g |
| Mean density | $5.49 \pm 0.05$ g-cm$^{-3}$ |
| Rotation period | $58.4 \pm 0.4$ sidereal days<br>$\doteq 0.664 \pm 0.004$ orbital period |

The mass and radius, and the density derived from them, are adopted from the extended ephemeridal analysis conducted by Ash et al. (Ref. 1) on most of the available optical and radar data on the ranges and motions of the terrestrial planets. The quoted errors are standard errors only, the nature of any systematic errors being at present unknown. Some concern for the possibility of significant systematic errors arises because of discrepancies between the Ash et al. values for the mass and radius of Venus and the more precise values (in the case of the mass at least) determined from the *Mariner II* and *Mariner V* near-Venus trajectory, the occultation experiment, and the U.S.S.R. *Venus 4* atmospheric parameters. However, it should be noted that the new values of the masses do not differ systematically from the most recently derived optical values.

The integral-fraction ratio of the Mercury day to its year has been explained by Goldreich (Ref. 2) in terms of capture into a resonant rotation mode by the action of tidal torques. This theory implies an explicit upper limit to the deformation of the planet, but one that is much larger than reasonable estimates of the actual value.

### B. Surface

Telescopically observed Mercury shows indistinct surface markings. The visual albedo, color index, polarization curves, phase integral, and radar reflection are similar to those of the Moon.

The temperature at the subsolar point, based on 8–14$\mu$ radiometric measurements, is 613°K at mean distance from the Sun. The midnight temperature is under 150°K. Brightness temperatures based on microwave emissions are:

| *Wavelength* $\lambda$, *cm* | $T_B$, °*K* |
|---|---|
| 11 | 300 (over large-phase range) |
| 1.9 | $288 + 75 \cos(\theta - 29°)$ |
| 0.34 | $277 + 97 \cos(\theta - 38°)$ |

The two phase-dependent curves are consistent with a model proposed by Morrison and Sagan (Ref. 3) based upon the following surface material parameters:

| *Parameter* | *Value* |
|---|---|
| Effective emission depth | 10 wavelengths |
| Dielectric constant | 2 |
| $\rho c$ | 0.3 |
| $(k\rho c)^{1/2}$ | 500 (typical of lunar surface material) |

### C. Atmosphere

Several investigators have recently produced data indicating that the atmospheric pressure of Mercury may be much less than the 1–5 mbar formerly believed, refuting earlier inferences of a 1–5 mbar surface pressure based on polarization curves and spectral data. For example, spectroscopic studies by Bergstralh, Gray, and Smith (Ref. 4) place an upper limit of 0.04 mbar on the partial pressure of $CO_2$.

## III. Prospects for New Information Prior to 1973

The Ash et al. (Ref. 1) values for the radius and mass are likely to be improved and their confidence level raised by removal of discrepancies in other parameters linked in the calculation.

Continued precise radar ranging with presently available apparatus may give the distortion of the Mercury equator. Significant Earth-based optical measurements of its shape do not seem likely.

Radio astronomical measurements at a variety of wavelengths augmented by IR radiometer scans should give somewhat improved figures for the dayside temperature distribution and the thermal properties of the surface material. However, determination of heat flow from the interior seems beyond the reach of these measurements.

Near-infrared spectra should give indications of the surface composition, possibly to the extent of suggesting the nature of the bulk material responsible for the high mean density.

"Seeing" limitations will probably preclude any significant improvements in photography of surface features. However, radar studies are likely to give considerable topographic information, some of it perhaps related to visible features.

Systematic longitudinal variations in surface properties will be of interest for correlation with longitudinal variations in thermal regime associated with the resonant rotation.

Better limits may be expected on atmospheric abundances based on interferometry (resolution $\sim 0.1$ cm$^{-1}$) of strong $CO_2$ bands and the search for other hypothetical constituents.

## IV. Questions Bearing on Solar System History

These questions are suggested as relating to the scientific goals of the first space mission to Mercury, but differences in importance have not generally been considered in this report.

(1) *What is the internal mass distribution?*

(a) Does Mercury have a core and, if so, is it liquid? Is there any magnetic field?

(b) What are the moments of inertia?

Precise measurement of the flyby trajectory will lead to an improved value for the mass, possibly the first mass determination not suspected of systematic error. If the miss distance is as small as one or two Mercury radii, the ratio of the principal moments of inertia may also be determined. It seems unlikely that this ratio can be found to a sufficient precision to have much significance, at least until an orbiter can be utilized. A simple magnetometer (on an appropriate trajectory) would reveal the nature of the magnetosphere and thereby indicate if Mercury has an inherent magnetic field (with implications for a liquid core), or a possible surface conductive layer.

(2) *What is the physical shape of the planet?*

Whole-planet pictures from a flyby television system (at *Mariner IV* resolution level) should give a significantly accurate measurement of the planetary figure. Radio occultation measurements could give an independent value for the radius.

(3) *What is the thermal regime and its history?*

(a) What are the sources of heat?

(b) What is the surface and subsurface temperature distribution?

(c) How has solar radiation affected the planet?

Landed measurements may be necessary for direct information concerning the thermal regime and history. However, the Moon should serve as a useful "calibrated" analogue for enabling reasonably safe inferences to be drawn on the basis of topographic data and perhaps surface composition. By 1973, advances in microwave theory may permit the derivation of the thermal gradient from long-wavelength flyby microwave measurements on the Moon, where landed measurements could verify the results.

(4) *What is the composition of the surface (including radioactive nuclides) and its petrologic nature?*

(a) Are high-density rocks present at the surface?

(b) Is the surface homogeneous?

Gross surface composition will be indicated by the emitted gamma-ray spectrum — both natural emissions and those induced by cosmic-ray bombardment. Calculations indicate that counting statistics would be adequate for a meaningful flyby gamma-ray spectrometer experiment, if the trajectory passed within about 4 Mercury radii of the center of the planet.

Near-infrared spectrometer measurements (or possibly a series of filtered photometers) would provide an indication of mineralogical and compositional variations over the dayside surface.

(5) *What is the nature of the topography?*

An imaging experiment would determine the shape of the planet, something about the topography, and other geologic features of the surface. Because of the possibly far-reaching ramifications of its results, this is an important experiment for a Mercury flyby mission.

(6) *What are the density and composition (including isotopes) of the Mercury atmosphere?*

The slight and tenuous atmosphere may offer clues to the internal composition and interior processes. However, determination of abundances and composition will probably require measurements from a landed spacecraft.

## References


1. Ash, M. K., Shapiro, I. I., and Smith, W. B., "Astronomical Constants and Planetary Ephemerides Deduced From Radar and Optical Observations," *Astron. J.*, Vol. 72, p. 338, 1967.

2. Goldreich, P., and Peale, S. J., "Resonant Spin States in the Solar System," *Nature*, Vol. 209, p. 1078, 1967.

3. Morrison, D., and Sagan, C., "The Microwave Phase Effect of Mercury," *Astrophys. J.*, Vol. 150, p. 1105, 1968.

4. Bergstralh, J. T., Gray, L. D., and Smith, H. J., "An Upper Limit for Atmospheric Carbon Dioxide on Mercury," *Astrophys. J.*, Vol. 149, L137, 1967.

# Jupiter

## I. Introduction

Jupiter would have to be ranked as one of the most interesting objects in the solar system if on no other basis than its great mass. Because of that mass (over 300 $M_E$), its gravitational field is likely to have been strong enough to have held most of its material, even the very lightest, since the time of Jupiter's formation. Its composition may therefore be more representative of the original matter from which the solar system was formed than those of the terrestrial planets.

Jupiter exhibits many outstanding features besides its great size. It is a dynamic planet, impressive in appearance, with a visible cloud surface of changing structure and color. The surface presents one particularly mysterious marking, the famous Red Spot, which seems to be unique in the solar system.

Jupiter is perhaps an even more interesting planet when observed in the nonvisual regions of the spectrum. Radioastronomers have discovered that it emits nonthermal radiation in the decimetric and decametric wavelength ranges. It is widely accepted that the decimetric waves are produced by trapped electrons moving in intense radiation belts within a strong Jovian magnetic field. Observations in the infrared seem to indicate that Jupiter radiates more energy than it receives from the Sun; in which case, the planet must contain an internal source of energy. Finally, around the planet circles the largest family of satellites in the solar system; two of which are more massive than the Moon, and as large as the planet Mercury.

In addition to possessing an apparently "primitive" or "unmodified" bulk composition, the planet excites interest because the composition is strongly reducing. This characteristic is not shared by other planetary surface environments, owing primarily to $H_2$ exospheric escape from them (coupled with possible biotic effects). In view of the fact that successful laboratory experiments in nonbiotic synthesis of high-molecular-weight organic compounds have always required high free-$H_2$ concentrations, the Jovian atmosphere is a site of prime interest for exobiological studies oriented toward understanding of the mechanisms of natural spontaneous life initiating reactions. It could be reasonably argued that such reactions could not effectively proceed on Jupiter because of the lack of liquid water or a solid surface – needed for polymerization and storage-concentration of products, respectively. On the other hand, some spectroscopic evidence has led to the suggestion that organic molecules may be a major constituent of the enigmatic Red Spot.

The basic physical data for Jupiter are summarized in Table 1, and discussed in more detail in the following sections.

**Table 1. Physical data for Jupiter**

| Characteristic | Value |
|---|---|
| Gravitational constant $GM_p$ | $1.267106 \times 10^8$ km$^3$-s$^{-2}$ |
| Mass (Earth = 1)[a] | 317.9 |
| Mean radius (Earth = 1)[b] | 10.97 km |
| Mean density | 1.35 g-cm$^{-3}$ |
| Oblateness | 1/15.4 |
| Bolometric albedo[c] | 0.45 |
| Average temperature[d] | 105°K |
| Brightness temperature (measured 8–14$\mu$)[c] | 127°K |
| Mean surface gravity (Earth = 1)[e] | 2.64 cm-s$^{-2}$ |
| Mean escape velocity | 60.2 km-s$^{-1}$ |

[a]$GM_{\oplus} = 3.986032 \times 10^5$.
[b]$R_{\oplus}$ = 6371 km.
[c]Terms defined in Appendix F.
[d]The temperature of a nonconducting body at Jupiter's mean distance from the Sun with the bolometric albedo as given, receiving radiation upon a projected area $\pi R^2$ but radiating from an area $4\pi R^2$ (the body rotates fairly rapidly).
[e]$g_{\oplus}$ = 982 cm-s$^{-2}$.

## II. Present Knowledge

In this section, references not specifically cited can be found in one of the general references.

### A. Atmosphere

*1. Composition.* Absorption bands in the spectrum of Jupiter were photographed by V. M. Slipher at Lowell Observatory shortly after the turn of the century; the bands were later found to be due to the presence of methane and ammonia. However, other data indicate that the bulk of Jupiter must be hydrogen and helium (see following Subsection B). Photoelectric observations of the occultation of $\sigma$ Arietis gave for the stratosphere an inverse scale height of 0.12 ± 0.04 km$^{-1}$, which corresponds to a mean molecular weight of 3.3 for an assumed stratospheric temperature of 86°K, consistent with the dominance of hydrogen and helium in the Jupiter atmosphere. Molecular hydrogen has also been detected spectroscopically.

It is extremely difficult to obtain accurate spectroscopic abundances for an optically thick atmosphere with an indefinite lower boundary; i.e., the cloud deck. However, a study by Field gives reasonable assurance that the $H_2$ abundance above the "reflecting layer" lies between 30 and 80 km-atm, "with some preference for the lower values." As for methane and ammonia, Kuiper estimates their abundances as 150 and 7 m-atm, respectively. Indirect spectroscopic evidence (pressure broadening of methane lines) indicates that the He:$H_2$ ratio is about 1:2, which gives a mean molecular weight agreeing within the probable error of that derived from the occultation measurement. Thermodynamic equilibrium calculations indicate that, in Jupiter's atmosphere, most of the carbon must be present as methane; most nitrogen, as ammonia; and most oxygen, as water. All water is frozen at the temperature of the visible part of the atmosphere, as indeed is much of the ammonia. Below the visible clouds, these substances may be present in liquid and vapor phases.

*2. Temperature and the energy balance.* An apparent discrepancy between energy absorbed by Jupiter from the Sun and energy emitted by the planet was discussed by Öpik in 1960 and again in 1962 (Ref. 1). The best bolometric albedo for Jupiter, 0.45, due to Taylor, implies that Jupiter should have an average temperature of 105°K. Brightness temperatures, measured at a number of wavelengths (see Appendix E) make it seem unlikely that the effective temperature can be as low as 105°K. The 17.5–25$\mu$ measurement is particularly important since it is near the maximum in the flux that would be emitted by a black or gray body at an effective temperature equal to the measured brightness temperatures (see part 4, atmospheric structure, of this subsection).

There are many possible sources of error in these results. Jupiter never exhibits a phase greater than 12 deg as seen from Earth. The phase integral must therefore be estimated theoretically from limb darkening curves. There are also errors in the measurement of the geometric albedo (see Appendix F). Taylor estimates the total uncertainty in the bolometric Bond albedo to be 15% (or 0.45 ± 0.07). An albedo of 0.38 would raise the equilibrium temperature to 109°K.

Jupiter rotates in less than 10 h. If the thermal relaxation time of the radiating "surface" of Jupiter is large compared with 5 h, it must radiate effectively from the total surface of the planet. If it relaxes to a very low temperature in much less than 5 h, then it effectively radiates only from the lighted hemisphere, in which the radiation balance temperature could be as much as $2^{1/4}$ greater than 105°K (or 125°K). These calculations have assumed a solar constant of 2 cal cm$^{-2}$-min$^{-1}$ at the Earth's mean distance from the Sun. However, the best existing curves of limb darkening for Jupiter indicate a temperature drop of about 5°K between disk center and a point near the limb, indicating a large atmospheric thermal inertia. Theoretical calculations agree that the atmosphere should cool slowly. The measured average brightness temperature then is about 123°K at $10\mu$ and more than 130°K at $20\mu$. An effective temperature of 125°K implies a contribution from an internal energy source of $7 \times 10^{3}$ erg cm$^{-2}$-s$^{-1}$, an amount of energy equal to that absorbed from the Sun (assuming the bolometric albedo of 0.45 is correct).

Nonsolar sources of energy external to the planet do not seem to be able to provide enough energy to account for the energy discrepancy. For example, a particle falling from infinity to the "surface" of Jupiter and releasing all of its kinetic energy at that point would supply $1.86 \times 10^{13}$ erg-g$^{-1}$. The apparent energy surplus then could be supplied by the infall of $3.85 \times 10^{10}$ g cm$^{-2}$-s$^{-1}$ of matter, $2 \times 10^{16}$ g-day$^{-1}$ over the entire planet (at 100% conversion efficiency). The meteorite mass incident on the Earth is typically estimated at $1\text{–}2 \times 10^{6}$ g-day$^{-1}$. A daily fall on Jupiter $10^{10}$ greater than that on Earth seems extremely unlikely, even considering its large gravity field and proximity to the asteroid belt.

A fundamental physical property of the planet Jupiter then is its emitted energy flux as a function of wavelength, phase, and local time of day. This flux can only be determined accurately from a spacecraft flying by or in orbit around Jupiter. If the emitted flux is indeed greater than the absorbed solar flux, this is a planetary problem of deep significance. Incidentally, Hubbard (Ref. 2) suggests that, if the excess exceeds $\sim 10^{3}$ erg-cm$^{-2}$, Jupiter must be wholly convective (fluid throughout). (See following Subsection B.)

**3. *The visible surface of Jupiter.*** The discussion of the present knowledge of the visible surface of Jupiter is presented under three groupings: rotation, clouds, and Red Spot.

*a. Rotation.* One of the remarkable facts of Jovian meteorology is that the clouds making up the visible surface rotate as two distinct systems. Points within about 10 deg of the equator constitute System I, the standard meridian of which rotates with a period of $9^h50^m30^s.003$ GMT. Points lying more than 10 deg from the equator in either hemisphere constitute System II, the standard meridian of which rotates with a period of $9^h55^m40^s.632$ GMT. Varying cloud motions relative to the standard meridians make it somewhat academic that the choice of a period for them be more exact than a whole second. Some exact standard is needed for reference, of course, and the exact numbers used have a historical significance.

It appeared for a time that the sources of decameter radiation were rotating with a *fixed* period differing slightly from both Systems I and II. A System III with a period of $9^h55^m29^s.37$ GMT was defined for this radiation and adopted by the International Astronomical Union.

Since 1961, the apparent rotation period of decameter sources has been about 0.8 s longer than System III. Since 1962, the rotation of the decimeter radiation (the planetary magnetic field) has been measured regularly, and its rate is within $\pm$ 0.5 s of System III.

It is difficult to define a unique rotation period unless a body has somewhere a solid surface, which Jupiter may or may not have. The period most likely to represent the rotation of the solid body with greatest accuracy would seem to be that in which the magnetic dipole rotates; that is, System III. But, if the planet proves to be fluid throughout, the concept of "true period" may be hard to define and of little value.

*b. The clouds.* It is generally accepted that the clouds of Jupiter are ammonia cirrus; that is, clouds of small particles of solid ammonia. It seems possible that part of the visible cloud deck reaches the melting point of ammonia (195°K), since the best proposal for explaining the observed decrease in ammonia and methane absorption from center to limb is that of a cumuliform cloud structure with the tops reaching 20–30 km above the main deck. If this explanation is true, the main deck could be as warm as 230°K, although a somewhat lower temperature seems more likely.

There are very definite color effects observed in the cloud belts: gray, brown, yellow, blue, and red. There are several speculations concerning the origin of the colors, the most recent being that they are complex organic compounds such as azulene, azobenzene, pyrene, coronene, and chrysene.

Detailed photography of the cloud structure from a close space probe flyby may greatly help understanding the complex Jovian meteorology. Understanding the colors may prove more difficult, since they seem likely to result from trace molecules.

*c. The Red Spot.* The most permanent feature on the visible surface of Jupiter is the famous Great Red Spot. This feature, an elongated oval some 40,000 km in length by 13,000 km in width, was definitely noted in observations of over 120 yr ago and probably was seen as long as 300 yr ago. The spot became most famous during the period 1879–1882 when its color was quite intense. Since that time, its visibility and color have waxed and waned. Although the color itself has disappeared entirely at times, the location of the spot has always been obvious. It was very prominent during 1962–63, for example. The really remarkable feature of the spot is that it seems not solidly attached to any fixed surface but rather has wandered more or less at random over a range covering 1200 deg of longitude (over three times around the circumference). In a recent period of seven months, the period of rotation of the Red Spot changed five times, varying between $9^h55^m40\overset{s}{.}4$ and $9^h55^m48\overset{s}{.}0$ GMT.

Older speculations on the nature of the Red Spot were variations on the theme of a solid island floating in a dense atmosphere. Increased knowledge of the physical conditions in the atmosphere of Jupiter has made such possibilities seem unlikely. In 1961, Hide proposed that the Red Spot might be the upper end of a "Taylor column," a stagnant column of fluid caused by a two-dimensional atmospheric flow associated with a "topographical feature." He attributed the gross motion in longitude to actual change in the period of rotation of an assumed mantle of Jupiter caused by hydrodynamic motions in the core. Of course, if Jupiter has no solid surface, the hypothesis seems more difficult to maintain.

***4. Atmospheric structure (models).*** Ignoring long-term temporal variations, an atmosphere is in a sense "defined" when composition and variables of state are known as a function of altitude for various latitudes and times of day. This "vertical picture" of an atmosphere ignores most meteorology, but "weather" is normally a superimposed variation of less than about 10% on the average condition (with the possible exception of phenomena involving condensables, such as water). A model attempts to account for a selected set of known observables in the simplest possible way. Only one model will be discussed here, that of Trafton (Ref. 3).

The dominant source of opacity to thermal radiation in Jupiter's atmosphere is molecular hydrogen, which had been overlooked prior to Trafton's recent work. The opacity determines the atmospheric temperature profile and, thereby, its structure. Unfortunately, two critical parameters that are needed to define the atmosphere of Jupiter are unknown: the $He:H_2$ ratio and the effective temperature. Neither quantity can be measured from the surface of the Earth. Limits can be placed on their values, however, from indirect observations, and these limits are cited above. The $He:H_2$ ratio of about 1:2, derived spectroscopically, requires an effective temperature of more than 130°K if 8–14$\mu$ limb darkening observations of the planet are to be matched. Such a temperature is in agreement with the brightness-temperature observations quoted in Appendix E, although not required by them. Such an effective temperature definitely requires an internal heat source, since it exceeds even the temperature that a black body would have at Jupiter's distance from the Sun.

As an example of the type of atmosphere to which the previous considerations lead, Trafton's model most nearly meets the conditions discussed and is given in Table 2.

**Table 2. Atmospheric structure model**

| Properties | Value |
|---|---|
| $H_2$:He | 1 : 1 |
| Effective temperature | 120°K |
| Boundary temperature (temperature at zero opacity, the stratospheric temperature) | 95.5°K |
| Temperature at the top of the convective zone (probably near the cloud tops) | 185°K |
| $H_2$ above the convective zone | 38 km-atm |
| Top of convective zone | 53 km below optical depth $5 \times 10^{-4}$ |
| Pressure at top of convective zone | ~ 1.7 atm |

In the zone where the temperature is below 115°K, the Jovian atmosphere is saturated with ammonia at low vapor pressure, and the ammonia contributes very little to atmospheric opacity. In the zone between 120 and 140°K, ammonia contributes significantly to opacity. Observations indicate cloud "surface" temperatures of 165°K in the $\lambda$6470 $NH_3$ band, 200°K in the 1.1$\mu$ $CH_4$ band, and 200–225°K in the 2.4$\mu$ $H_2$ band; the increasing temperatures indicate penetration to increasing cloud depths. The model suggests that the clouds have considerable vertical structure and extent. With an internal energy source, the temperature would probably continue to increase with depth rather than tend to a constant value below the level to which solar radiation penetrates.

With present knowledge, it is not possible to describe atmospheric conditions below the clouds. Our best guesses are by-products of the planetary-interior models discussed in the next subsection.

### B. The Body Structure of Jupiter

Any theory of the interior of Jupiter must be dominated by one central fact: the mean density of the planet is only 1.35. Among all solid substances, only hydrogen and helium have densities low enough to make up the bulk of such a planet. For several decades, models of Jupiter have been constructed using various ratios of hydrogen and helium as a function of depth and using the best available theoretical equation of state for these elements, in addition to the assumption of hydrostatic equilibrium. The boundary conditions are set by the observed mass, oblateness, and gravitational multipole moments determined from the motions of the satellites. The very low-density outer layer (the atmosphere) has a large effect upon the higher order gravitational multipoles. The hydrogen-helium ratio is usually carried as an unknown and is allowed to vary with depth in the more recent models.

The biggest problem in these models is that of a suitable equation of state for hydrogen at pressures all the way up to $2 \times 10^{8}$ bars. Experimental data on the densities of solid hydrogen and helium at 4.2°K extend only to about $2 \times 10^{4}$ bars. In 1935, Wigner and Huntington recognized theoretically that, at an elevated pressure (now given as $0.7 \times 10^{6}$ bars), solid molecular hydrogen should undergo a change to a metallic phase. These calculations were made for 0°K. There may also be other phase transitions about which nothing is yet known.

In earlier work on structural models, it was thought that the thermal conductivity of solid hydrogen at low temperatures was so high that a planet composed of it could not support a large temperature gradient between its center and surface. Recently, Hubbard (Ref. 2) has restudied various high-pressure properties of hydrogen that are important in model calculations. He finds that the thermal conductivity of hydrogen has been greatly overestimated for realistic temperatures, and that central temperatures for Jupiter must be quite high ($\sim 10^{4}$°K) with energy transport dominated by convection, if the energy flow from the interior of Jupiter is $\sim 10^{3}$ erg $cm^{-2}$-$s^{-1}$ or more. Assuming the "base" of the atmosphere is at 85% of the radius (from the center) and at a temperature of 2000°K, the planet is wholly convective for internal energy fluxes greater than 2000 erg $cm^{-2}$-$s^{-1}$.

A current "best" model of Jupiter then might envision a central liquid core of 10% of the radius, a metallic hydrogen lattice that is nevertheless convective out to 80% of the radius, and a fluid atmosphere of molecular hydrogen above this. The temperature gradient might be adiabatic throughout with temperatures of 165–225°K at the cloud deck, 2–3 × $10^{4}$°K at 80% of the radius, and 9–10 × $10^{4}$°K at the center of the planet. The overall abundances by mass might be 76% hydrogen, 22% helium, and 2% heavier elements. The values given here do not exactly fit any of the models of de Marcus, Peebles, or Hubbard, but are typical of current thinking. Accurate values for the effective temperature of Jupiter (giving the internally generated energy flux) and for its hydrogen to helium ratio will allow more well-founded models to be derived. These will be highly relevant to any theory of the origin of the major planets.

### C. Radio Frequency Radiation

Radio radiation from Jupiter at a frequency of 22 MHz (decameter) was first reported in 1955 by Burke and Franklin. Reports on centimeter and decimeter radiation followed in 1959. The decameter radiation appears to originate in sources localized on Jupiter and is sporadic except possibly at frequencies below 15 MHz. The centimeter radiation is partially thermal in origin. Additional centimeter and decimeter radiation originates in a system of radiation belts around Jupiter.

*1. The decameter radiation.* In the years since its discovery, the behavior of the decameter radiation has become relatively clear, although the mechanism of its generation is still quite vague. The decameter flux often exceeds $10^{-20}$ W $m^{-2}$-$Hz^{-1}$, and emission has been observed from 7 m (43 MHz) to more than 60 m (5 MHz). Statistically, the emission varies with a period near (but not exactly equal to) the rotation period of Jupiter's equatorial system. The decameter radiation was given its own official rotational period (System III) of $9^{h}55^{m}29\overset{s}{.}37$; but since 1960, that period has appeared to be increasing by 1.176 s-$yr^{-1}$. Very recent work indicates that the drift varies somewhat with observing frequency and from source to source. Radiation beaming effects are suspected of playing a role here.

At frequencies below 15 MHz (20 m), the emission is often very broadband; while above 15 MHz, it is frequently quite narrowband with bandwidths only a few percent of the central frequency. Radiation above 18 MHz is dominantly right elliptically polarized at all longitudes. Emission sources appear to be localized on Jupiter. The most important sources are called the "early source," which occurs when radio longitude (System III) near 140 deg makes its central meridian passage (CMP), and the "main source," which occurs near CMP 240 deg. Lesser sources at 340 and 40 deg are the "late or third source" and the "fourth source," respectively. An unusual additional aspect was discovered in 1964 when Bigg found that Io (the first Galilean satellite) strongly modulates the emission above 20 MHz. Also, some modulation appears below 20 MHz. There is evidence that Jupiter is a continuous source of low frequencies (below 15 MHz), and that the Io effect may appear only in the intensity of the emission.

The entire mechanism of creation of the decameter radiation is still in a highly speculative state. Major facts that are needed to solve the problem include the exact nature of the Jovian magnetic field (its strength, location, and character), the location of the decameter sources, a lower limit on the frequency of the emitted radiation, and some knowledge of the electromagnetic properties of Io. All of these now appear to be determined best by means of spacecraft investigation.

*2. The centimeter and decimeter radiation.* Electromagnetic radiation at wavelengths shorter than 1 cm is entirely thermal in origin. A summary of such thermal radiation is given in Appendix E. At wavelengths from about 1–6 cm, the radiation is partially thermal and partially non-thermal, but dominated by the thermal component. Beyond 6 cm, the non-thermal emission seems to be constant (based on observations at 10, 11, 21, 31, 74, and 100 cm). The degree of linear polarization is constant at about 22%. Interferometric observations at 10.4 and 21.2 cm indicate that the radiation is coming from an area much larger than that of the planetary disk, the equatorial diameter of measured radiation at 10.4 cm extending to 4.0 arc-min at opposition distance. Jupiter's diameter at that time is 0.8 arc-min. Detailed brightness contours are given by Berge.

Morris and Berge discovered, in 1961, that the direction of polarization of the decimeter radiation was not constant, but rocked through about ± 10 deg with respect to the rotational axis of Jupiter. The decimeter radiation "is strongly beamed in the plane of the magnetic equator" and varies "as the magnetic axis apparently rocks to and fro." The rotation period, based upon this rocking, is within 0.5 s of the System III period.

All indications are that the non-thermal centimeter and decimeter radiation is synchrotron radiation from a Jovian trapped radiation belt.

*3. The magnetosphere.* The evidence for a Jovian magnetosphere consists entirely of the observations of Jupiter at microwave frequencies discussed in the previous parts of this section. Jupiter's magnetic field is substantially dipolar, with its axis inclined by 10 ± 0.5 deg to the axis of rotation and its north pole at the System III longitude of 190 deg. The quadrupole moment is perhaps a few percent of the dipole moment. Whether the field is body centered or somewhat displaced is strongly disputed, but the displacement would seem to be at most a small fraction of the radius. The field strength is unknown, but must be $\gtrsim$ 10 G at some point. It must be $\lesssim$ 50 G at points within the radiation belt. Field strengths of 10–20 G at the surface are often quoted.

Trapped particle fluxes are very difficult to estimate, but a lower limit to the peak flux of about 10 electrons $cm^{-2}$-$s^{-1}$ with energies between 5 and 100 MeV seems reasonable. This energetic electron flux appears to peak in a zone about 3 radii from the center of the planet, and the belt extends out to at least about 10 radii. It is impossible to detect lower energy electrons from Earth at the present time, and the flux of these may be several orders of magnitude higher than that of the energetic electrons given above. Similarly, protons cannot be detected from Earth, but it is reasonable to assume that they are present in the Jovian radiation belts. Estimates of the proton flux can be made by scaling the Earth's proton flux and taking into account the relative magnetic field strengths. Such calculations give proton fluxes of about $10^9$ protons $cm^{-2}$-$s^{-1}$ with energies between 0.1 and 4 MeV, but these numbers must be considered as purely conjectural at best.

If this account of the Jovian magnetosphere seems rather indefinite and incomplete, then it accurately reflects the state of knowledge on the subject. Knowledge will improve with improved ground-based radio telescopes, but any reliable solution must wait until field and particle measurements are made by space probes.

## D. The Satellites

From the viewpoint of celestial mechanics, there are two types of satellites: regular and irregular (plus the Moon, which belongs to neither class). Regular satellites are characterized by direct motion in nearly circular orbits

**Table 3. Orbital elements of Jovian satellites**

| Satellite | Semimajor axis, $10^3$ km | Eccentricity | Inclination[a] | Sidereal period, GMT |
|---|---|---|---|---|
| J V | 181.5 | 0.0028 | $0°27'.3$ | $11^{h}57^{m}22^{s}.70$ |
| J I (Io) | 422 | 0.0000 | $0°1'.6$ | $1^{d}18^{h}27^{m}33^{s}.51$ |
| J II (Europa) | 671.4 | 0.0003 | $0°28'.1$ | $3^{d}13^{h}13^{m}42^{s}.05$ |
| J III (Ganymede) | 1,071 | 0.0015 | $0°11'.0$ | $7^{d}3^{h}42^{m}33^{s}.35$ |
| J IV (Callisto) | 1,884 | 0.0075 | $0°15'.2$ | $16^{d}16^{h}32^{m}11^{s}.21$ |
| J VI | 11,487 | 0.158 | $27°.6$ | $250^{d}.57$ |
| J VII | 11,747 | 0.207 | $24°.8$ | $259^{d}.65$ |
| J X | 11,861 | 0.130 | $29°.0$ | $263^{d}.55$ |
| J XII | 21,250 | 0.169 | 147° | $631^{d}$ |
| J XI | 22,540 | 0.207 | 164° | $692^{d}$ |
| J VIII | 23,510 | 0.378 | 145° | $739^{d}$ |
| J IX | 23,670 | 0.275 | 153° | $758^{d}$ |

[a]To equatorial plane of Jupiter. Eccentricities and inclinations for regular satellites are slightly variable; those for irregular satellites are extremely variable.

almost in the equatorial plane of their primary; irregular satellites, by either direct or retrograde motion of almost any eccentricity and inclination. Jupiter has 12 known satellites: a group of five regular satellites near the planet and groups of three and four irregular satellites at a great distance. This arrangement is best shown in Table 3 which lists the orbital elements of the Jovian satellites.

*1. The irregular satellites.* The motion of the first group of irregular satellites at about 11,000,000 km is direct; that of the second group at about 23,000,000 km is retrograde. Kuiper feels this relationship is more than fortuitous and may well indicate a common origin for the members of each group, perhaps from one body.

Nothing is known about the rotation periods of any of the irregular satellites. If they rotate slowly enough, they could give Pluto competition for the title of the coldest spot in the solar system. Many have quoted Nicholson's remark that the outer satellites of Jupiter are so small and far from the planet that a 6-in. telescope would be needed to see them from Jupiter itself. Albedo diameters (except as calculated from brightness with an assumed albedo), densities, masses, and shapes of the irregular satellites are all unknowns and are likely to remain so until these bodies are explored by space probes.

*2. The regular satellites.* Jupiter's regular satellites consist of the four large Galilean satellites (giving Galileo credit for their discovery in 1610) and the much smaller Jupiter V, sometimes called Amalthea, discovered by Barnard in 1892. Observations of surface markings suggest that the Galilean satellites keep one face toward Jupiter; that is, their periods of rotation and revolution are synchronous. The light curves of these bodies show a single maximum and minimum in each revolution about their primary, as might be expected for synchronous behavior. The markings bear considerable resemblance to lunar maria.

Io is in many ways the most unusual of the Galilean satellites. Besides its dramatic effect on the decameter radiation (see previous Subsection C-1), which probably results from its location in Jupiter's magnetosphere, the satellite has other interesting properties. It is distinctly orange in color and much redder than the other Galilean satellites. Furthermore, photometric studies show that, when Io reappears after solar eclipse by Jupiter, it is on the average 0.09 magnitudes brighter than normal, this effect decaying in about 15 min. No such effect is observed before ingress to eclipse. A plausible explanation proposed is that Io has an atmosphere that begins to freeze out during the lower temperature period of eclipse and then returns to gaseous form upon heating by the Sun. Either methane or molecular nitrogen has thermal properties suitable for such an effect. Other explanations, such as color changes of a temperature-sensitive free radical on the surface, are quite possible. A large number of astronomers have searched spectroscopically for evidence of an atmosphere on Io, but as yet with negative results.

Europa exhibits a total variation in visual magnitude larger than Io ($\Delta V = 0.34$). A single photometric search for an eclipse effect similar to that of Io gave negative results. Ganymede, the largest of the Galilean satellites, with greater diameter than Mercury, has given no spectroscopic evidence of an atmosphere. Callisto is unusual in that it shows little variation in brightness with orbital phase with solar phase angle $< 1.5$ deg, but shows as much as 0.18 magnitude for solar phase angle $\sim 10$ deg. It shows little color change at any time and also no spectroscopic evidence for an atmosphere.

The Galilean satellites are important bodies of the solar system about which little is known or is likely to be known without space probe scrutiny. Ultimately, they must be given serious consideration as objects for major scientific study.

## III. Prospects for New Information Prior to 1973

Within the next five years, brightness temperatures of Jupiter will probably be measured at new wavelengths between 1 mm and 20 cm. New radio interferometric measurements should greatly improve positional knowledge of decimeter and decameter radiation. New spectroscopic information from interferometry in the $1\text{–}4\mu$ region can be anticipated. Improved temperature mapping in the $8\text{–}14\mu$ region is possible.

Theoretical advances in a number of areas seem feasible; for example, spectral interpretation (especially $CH_4$), model atmospheres (including dynamical meteorology), model interiors, and properties of $H_2$, He, etc., at very high pressures and non-zero temperatures. Direct measurements by a Soviet space probe might be made before 1973, but the likelihood of such an event is unknown.

## IV. Questions and Space Experiments for the 1970s

The anticipated measurements discussed in Section III. should obviously provide information of great importance and interest, but it is doubtful whether any of the following scientific questions will be answered in sufficient depth by such measurements. The questions in this section are, therefore, suggested as a basis for choosing experiments in early space missions to Jupiter. Each question is followed by a discussion of its scientific importance and the experimental measurements relevant to it.

### A. Questions Bearing on Solar System History

(1) *What are the relative abundances of H, D, He, Ne, and other elements?* These may well represent the abundances in the original solar nebula at Jupiter's distance from the Sun, since even the lightest molecules would be captured in so strong a gravitational field.

Flyby or orbital occultation would give the H to He ratio, assuming that the contribution of heavier elements to the mean molecular weight is negligible. Flyby or orbital UV spectroscopy would give the abundances of elemental gaseous components. A simple flyby or orbital UV photometer could make highly important H and He abundance measurements. Mass spectroscopy from an entry probe would probably be the best approach. There is a general difficulty with sampling for the elemental abundance measurements, particularly for nongaseous components.

(2) *What are the abundances of Li, Be, and B?* These would set upper limits on how hot Jupiter has ever been. (Have they been burned?) Abundances of certain isotopes could allow more refinement on this maximum temperature.

These elements are not normally gaseous. Sampling is a problem and measurements are difficult. Mass spectroscopy from a deeply penetrating probe is probably the best plan, but even this may not be sufficient.

(3) *Does Jupiter radiate more energy than it receives from the Sun and, if so, how much more?* The answer to this question, together with improved data for internal models, may well determine whether the planet is fluid or solid throughout most of its bulk, which in turn would be relevant to its evolutionary history. As a related question, does Jupiter have a solid surface?

Flyby or, preferably, orbital IR and visible radiometry ($0.2\text{–}50\mu$ range) to measure the total energy flux over all latitudes and longitudes is desired here.

(4) *What are the present-day atmospheric composition and altitude profiles of pressure, temperature, and density, and what effect do they have on the radiation balance?* These serve as an upper boundary condition for some interior models. From the actual elements involved (alone and in compounds), atmospheric composition may also give relative

elemental abundances of the solar nebula, if the planet is well mixed.

Experiments, as under question (1) above, would give elemental and diatomic-molecular abundances. Flyby or orbital high-resolution IR spectroscopy or interferometry would give abundances of polyatomic molecules. Gas chromatography from an entry probe could detect selected constituents including organic compounds. Temperature, pressure, density, and composition profiles are best measured on an entry probe.

### B. Questions Bearing on Exobiology

(1) *Do complex organic molecules exist in the atmosphere of Jupiter?* Laboratory experiments have shown that electrical discharges in a mixture of gases corresponding to those identified in Jupiter's atmosphere produce complex organic molecules that are fundamental components of living organisms.

High-resolution IR spectroscopy or interferometry from a flyby or orbiter, and gas chromatography from an entry probe would give data of interest here.

### C. Supplementary Questions

(1) *What are the nature and origin of the decameter radiation?* Flyby or, preferably, orbital mapping to locate the sources, define their structure, and determine their full frequency range of emission would be desirable here.

(2) *What is the source (origin) of the large planetary magnetic field?* This question could be related to those bearing on solar system history. What relationship does the field have to the origin of the planetary radio emissions (particularly the decameter radiation)?

Flyby or, preferably, orbital mapping of the field correlated with mapping of the decameter sources would be of interest.

(3) *What are the fluxes, energy spectra, and spatial and time variations of the particles in the radiation belts?* A comparison of the Jovian belts with those of the Earth may clarify the particle acceleration processes common to both. Data on the Jovian belts are of obvious interest as environmental information for future space probe design.

Flyby and orbital energetic electron and proton measurements over as wide an energy range as possible are required.

(4) *What are the nature and origin of the Great Red Spot?* High-resolution imagery, IR radiometry, spectroscopy, and interferometry data on the Red Spot from a flyby or orbiter compared with similar data from other parts of the planet would be of interest. Doppler data (for example, in the visible or IR) on the Red Spot relative to similar data from the rest of the planet would be useful in measuring internal motions.

(5) *Is there a "true" period of rotation of Jupiter?* Why does the atmosphere rotate in two distinct systems? How can the Red Spot and the decameter sources change their apparent period of rotation?

The answer to this question hinges on a better understanding of the structure and atmospheric dynamics of the planet. Therefore, many measurements listed elsewhere are relevant here, if only indirectly.

(6) *What are the nature and origin of the colors observed in Jupiter's atmosphere?* Flyby or orbital high-resolution IR spectroscopy, or interferometry, or entry gas chromatography to search for selected organic compounds would be useful here.

### D. Satellites

*1. Questions bearing on solar system origin.*

(1) *Are the Galilean satellites elementally similar to their primary except for the escape of the lighter gases?* To what extent do they resemble the Moon?

IR reflection spectroscopy from a flyby will give some hint of surface composition. A lander is required to make definitive measurements by means of such techniques as alpha-scattering or X-ray spectroscopy.

(2) *Are the two groups of irregular satellites captured asteroids?* Were they lost as proto-Jupiter lost mass and then recaptured? Were there only two bodies involved which subsequently broke up into groups of three (or more) at $11.5 \times 10^6$ km and four (or more) at $23 \times 10^6$ km?

Comparative data, such as imagery and composition of the satellites and asteroids, are required.

(3) *What are the mean densities of the eight small satellites?* A close flyby to give the mass (perhaps an orbiter is required) plus imagery to give the size are needed.

(4) *What are the dynamic and optical flattenings of the Galilean satellites?* An orbiter to get the dynamic flattening plus imagery to get the optical flattening are required.

(5) *What do they look like?* Can any history of the Galilean satellites be read from their surfaces? Flyby or orbital imagery is required.

(6) *Do the satellites have magnetic fields?* Such information will have implications regarding internal structure. Io is of particular interest here, in that one theory explains Io's modulation of the decameter radiation on the basis of an interaction between a proposed satellite field and the main Jovian field.

Magnetic field mapping from a flyby or orbiter is required.

2. *Supplementary questions on satellites.*

(1) *Do the Galilean satellites have atmospheres?* If so, what is the composition and amount of atmosphere? Only Io has given evidence of an atmosphere, and that evidence is only photometric, not spectroscopic.

Flyby occultation and high-resolution IR spectroscopy, or mass spectroscopy from a close flyby or orbiter or a lander would give data on composition. Imagery to show hazes or scattering effects, or polarimetry to detect scattering could be performed from a flyby or orbiter.

(2) *What causes the peculiar orange color of Io?* Refer to questions (5) of D-1 and (1) of D-2 above.

## References


1. Öpik, E. J., "Jupiter: Chemical Composition, Structures, and Origin of a Giant Planet," *Icarus*, Vol. 1, pp. 200–257, 1962.

2. Hubbard, W. B., "Thermal Structure of Jupiter," (preprint, Aug. 1967).

3. Trafton, L. M., "Model Atmospheres of the Major Planets," *Astrophys. J.*, Vol. 147, p. 765, 1967.


## General References


Michaux, C. M., *Handbook of the Physical Properties of the Planet Jupiter*, NASA SP-3031. National Aeronautics and Space Administration, Washington, D.C., 1967.

Warwick, J. M., "Radiophysics of Jupiter," *Space Sci. Rev.*, Vol. VI, p. 841, 1967.

# Appendix A

## Scientific Expectations of *Mariner* Mars 1969

*E. Miner*

### I. Summary of Science Payload and Objectives

Table A-1 summarizes the scientific objectives and salient instrument characteristics of the experiments to be conducted by the *Mariner* Mars 1969 spacecraft. The next section describes the planned operation of the instruments and gives some of the results expected from the experiments. The final section suggests some of the possible implications of the results for the Martian scientific questions discussed in the Mars chapter.

**Table A-1. Summary of science payload and objectives**

| Experiment | Instrumentation | Objectives |
|---|---|---|
| Visual imaging | Vidicon (camera A); 11 × 14-deg field-of-view; alternating red and green filtered pictures<br>Vidicon (camera B); 1.1 × 1.4-deg field-of-view; blue cutoff filter to reduce haze | Primary:<br>a. To record surface and atmospheric features over much of planet at a resolution significantly better than that obtainable from the ground<br>b. To categorize topographically the basic light and dark areas and perhaps learn more about why they undergo seasonal variations<br>c. To further explore this unknown planetary surface for additional clues as to its origin<br>d. To obtain sufficient coverage at a suitable resolution to distinguish, on the basis of crater morphology and other criteria, between an episodic and a continuous history<br>Secondary: It has been proposed that TV imaging of the planet be undertaken 72–80 h before encounter and that these pictures be returned to Earth prior to encounter; these proposed alternate far-encounter sequences are directed toward the following secondary objectives:<br>e. To obtain a precise measurement of radius and figure of Mars<br>f. To obtain data concerning cloud and haze conditions as a function of height, both planet-wide and on a small scale; thereby, enhancing our knowledge of meteorological conditions on Mars<br>g. To obtain data about the sizes, shapes, and orbits of one or both of the satellites of Mars |
| Infrared radiometer | 8–12$\mu$ radiometer (channel 1); 0.7 × 0.7-deg field-of-view; boresighted with TV<br>18–25$\mu$ radiometer (channel 2); 0.7 × 0.7-deg field-of-view; boresighted with TV | a. To measure IR emission from area of Mars scanned by television subsystem to obtain a temperature map that can be correlated with topographic or cloud features observed visually<br>b. To obtain a surface cooling curve in a scan approximately perpendicular to terminator<br>c. To obtain temperature measurements of dark-side surface that is inaccessible from Earth |

Table A-1 (contd)

| Experiment | Instrumentation | Objectives |
|---|---|---|
| Infrared radiometer (*contd*) | | d. To obtain absolute temperature measurements of south polar cap to differentiate between $CO_2$ and $H_2O$ caps |
| Infrared spectrometer | HgGe detector (channel 1); 4.0–14.3$\mu$ spectrum; 0.01 wavelength resolution; 0.057 × 2.1-deg field-of-view<br>PbSe detector (channel 2); 1.9–6.0$\mu$ spectrum; 0.01 wavelength resolution; 0.057 × 2.1-deg field-of-view | a. To ascertain presence of polyatomic molecules that suggest biochemical processes, affect ambient surface temperature, and limit UV flux at surface<br>b. To determine compositional variations of atmospheric constituents relative to geographic locale<br>c. To obtain data concerning surface composition, gas temperature, surface albedo, and surface temperature |
| Ultraviolet spectrometer | CsI photomultiplier tube (channel G), 1800–2200 Å (first-order spectrum); 1100–2150 Å (second-order spectrum); 20-Å resolution in first-order spectrum; 0.229 × 2.29-deg field-of-view<br>Bi-alkali photomultiplier tube (channel N), 1900–4300 Å (first-order spectrum); 1500–2150 Å (second-order spectrum); 20-Å resolution in first-order spectrum; 0.229 × 2.29-deg field-of-view | a. To detect presence of atoms, ions, and molecules in upper atmosphere of Mars<br>b. To measure scale height of these atmospheric constituents<br>c. To measure Rayleigh scattering from lower atmosphere and UV reflectivity of planetary surface |
| S-band occultation | No special spacecraft equipment other than existing S-band radio subsystem | a. To determine pressure and density in atmosphere of Mars and their variation with altitude, and to observe possible variations with latitude<br>b. To determine electron density profile of ionosphere of Mars<br>c. To obtain precise measurements of radius of Mars at four points on its surface |
| Celestial mechanics | No additional equipment is required beyond that existing for radio tracking purposes | To improve accuracy of determination of significant astrodynamic constants including mass of Mars, mass of Moon, astronomical unit and other parameters that will improve ephemerides of Earth and Mars; investigation of relativistic effects on orbit will be explored |

## II. Expected Results by Experiment

The alphabetic-identified paragraphs in this section are keyed to the experimental objectives given in Table A-1.

### A. Visual Imaging

During encounter, the smallest wide-angle TV (camera A) surface coverage per frame will be of the order of 700 × 900 km with a resolution of 1.0 km per TV line. These pictures will be taken alternately through red and green filters, and there will be considerable overlap between successive wide-angle pictures. The narrow-angle TV (camera B) will be centered on these regions of overlap and will provide high-resolution views of small areas whose general characteristics are defined in the wide-angle pictures. A blue cut-off filter will reduce atmospheric haze effects in the camera B pictures. At a range of 3000 km, the camera B coverage corresponds to a surface area of the order of 70 × 90 km with a resolution of 0.1 km per TV line. The time between pictures is 42.24 s. For each spacecraft, each camera will take about 12 pictures, or a total of 24 wide-angle and 24 narrow-angle frames during near-encounter phases.

| *Key* | *Expected Results* |
|---|---|
| a, b | It is difficult to predict just what the TV cameras will see on Mars. The best resolution will be about 100 meters (per TV line), making it unlikely that large boulders could be detected. |

Stereoscopic viewing of areas of overlap in the wide-angle photos should allow some estimates of gross surface elevation differences (and cloud heights) to be made. Contouring by use of a Martian surface photometric function (as was done with the *Ranger* pictures for the Moon) to provide more precise elevation differences, might be possible if an adequate photometric function can be determined.

c, d Craters, fault lines, and other structural patterns will give an indication of the past history of the planet and perhaps of its present internal activity. It might be possible (though the probability is small) to detect volcanic activity. Distortion or relative "freshness" of craters will help to distinguish between a steady-state (or continuous) history and an episodic history. There will also be a sufficient number of "canals" photographed to determine their reality as surface features, and perhaps their physical characteristics.

The current plan for far-encounter photography is to take 8 pictures at approximately 4-h intervals, starting 40 h and ending 12 h prior to encounter. This plan permits coverage of all parts of the planetary surface (except the north polar region). This plan and the proposed alternate far-encounter sequences involve only the narrow-angle TV (camera B). It would be well to note that no digital data will be recorded during far encounter (i.e., only the analog tape recorder will be used). The resulting pictures will consequently lack the photometric calibration of the near-encounter pictures. Implementation of one of the alternate far-encounter proposals would increase the number of returned far-encounter pictures from the present 8 to a total of either 72 or 96, depending on which plan is adopted.

| *Key* | *Expected Results* |
|---|---|
| e | With a sufficiently large number of pictures of the entire planet, it may be possible to measure the polar radius of Mars to within one part in a few thousand, and the equatorial radius and figure of Mars to a somewhat lesser accuracy. This measurement, in turn, could aid in the analysis of the S-band occultation data. |
| f | Some meteorological studies may be possible. Data concerning cloud and haze conditions as a function of height, both planet-wide and local, might be obtained. The hourly development of clouds could provide important clues as to the presence of biologically interesting areas. |
| g | The possibility exists of observing one or both of the satellites of Mars at a useful resolution, sufficient to reveal something of their sizes and shapes and possibly to improve the values of their orbital parameters. At encounter minus 12 h, Phobos would cover at most 4 pixels and Deimos 1 pixel of the narrow-angle TV. (Each TV frame is composed of an array of 704 $\times$ 945 pixels = picture elements.) If the satellites could be photographed at just 4 h before encounter (as proposed in one of the alternate far-encounter sequences), Phobos might cover from 16 to 41 pixels and Deimos from 4 to 10 pixels. Information about the sizes of the satellites would in turn provide information about their albedos. |

### B. Infrared Radiometer

The expected range of Martian surface temperatures is within the limits of $145°K \leq T \leq 310°K$. At the lower limit, the radiometer resolution will be $\pm 0.4°K$ per digitization level; at the upper limit, it will be $\pm 0.06°K$ per digitization level. The errors quoted apply naturally only to effective black-body temperatures. Actual surface temperatures will be far less accurately determined due to our lack of knowledge of the Martian surface emissivity. The field-of-view of the IRR corresponds to about 36 $\times$ 36 km at the surface of Mars for a spacecraft altitude of 3000 km. The sampling rate is 1 sample every 2.1 s for each channel. The spacecraft velocity relative to Mars will be about 8 km/s at encounter. Thus, there will be considerable overlap in the successive samples.

| *Key* | *Expected Results* |
|---|---|
| a | The IRR experiment will be able to assist in ascertaining the nature of special features detected in TV images. As an example, light areas were observed around some craters in the *Mariner IV* TV pictures of Mars. If the IRR scans across similar features during the 1969 encounter and if they have a scale of about 10 km, differentiation between true ground features and remnants of $CO_2$ or $H_2O$ ices will be relatively simple. The identification of cloud features of various kinds will also be facilitated. Aside from special features, it is likely that the IRR will show that the daytime temperatures of the dark areas are from 5 to 10 deg warmer than adjacent light areas. |

b, c In a scan perpendicular to the terminator, the temperature will probably be $295 \pm 15°K$ near the subsolar point and will drop to $210 \pm 25°K$ at the terminator. On each of the two *Mariner* Mars 1969 spacecraft, the IRR will continue to scan the dark side of Mars for several minutes, reaching points on the surface which are 3–4 h past local sunset. For a thermal-inertia parameter $(k\rho c)^{1/2}$ of 0.004 cgs units, the temperature at these points would be $180 \pm 10°K$. Since Earth-based measurements limit the range of thermal inertia parameters for Mars to $0.001 < (k\rho c)^{1/2} < 0.01$, the uncertainty in the minimum temperature sensed past the terminator is larger, and $T = 180 \pm 30°K$ could be expected at these points.

d At the pressures expected at the Martian surface, carbon dioxide will sublime at $150 \pm 5°K$. Through direct measurement of the thermal emission from the southern polar cap, it will be determined whether or not the temperature is low enough to allow $CO_2$ ice formation. If not, it is likely that the polar caps are formed of $H_2O$ ice. This simplified differentiation may be complicated considerably if the caps have heavy cloud cover, but a combination of *Mariner* Mars 1969 TV and ground-based visual observations should allow one to ascertain the degree to which cloud cover influences the measurements. It should be noted that only one of the two spacecraft will fly over the polar cap.

### C. Infrared Spectrometer

The IRS data to be taken will start when the projected slit image is about 400 km above the lighted limb of Mars. This starting height will enable the experimenters to determine how much scattered light will affect the readings on the planet. One complete spectrum is made every 10 s by rotating a circular variable interference filter disk in front of the light beam. Each spectrum scan consists of 1332 samples, 666 per channel. There is double coverage of the 4.0–6.0$\mu$ spectral range. The projected slit images for the two channels are not superimposed, but are aligned end to end, with about 14% overlap. At a range of 3000 km, each slit subtends a surface area of $3 \times 108$ km.

| *Key* | *Expected Results* |
|---|---|
| a | The 1.9–14.3$\mu$ region of the spectrum contains the more intense characteristic absorptions of all organic molecules. In particular, methane, ethylene, acetylene, and methanol will be looked for, as well as $N_2O$, NO, $NO_2$, $NH_3$, CO, $C_3O_2$, $O_3$, $H_2O_2$, $SO_2$, and $H_2S$. The last two, if detected in the Martian atmosphere, may be indicative of volcanic activity on the planet. The experimenters estimate that they should be able to detect the organic molecules in atmospheric concentrations as small as 2 ppm (assuming a 10-mbar surface pressure). In this spectral region there are also some absorption lines of $CO_2$ and $H_2O$, both of which are known to exist in the Martian atmosphere. Some of the above molecules (such as $O_3$) are strong absorbers of UV radiation, and knowledge of their quantities from IRS and UVS data could provide information about the amount of UV radiation actually reaching the Martian surface. Knowledge of the atmospheric constituents will also provide a means of calculating the effect of solar radiation on the ambient surface temperature of Mars. |

| *Key* | *Expected Results* |
|---|---|
| b | For carbon dioxide and water, the band contours will be related to the temperature–pressure profile of the atmosphere. It is hoped that comparison among band contour data, atmospheric composition data at various places on the surface, and data generated from various atmospheric models may show differences that would aid in discerning the nature of the light and dark areas and their elevations, and the dependence of atmospheric phenomena on longitude or latitude. Locales of unusually high humidity – favorable for future landed life-detection experiments – would be considered unusually valuable discoveries. |
| c | If one subtracts the effects of the atmosphere from the spectra obtained, the remaining background radiation is due to the surface temperature (plus reflected sunlight below about 4$\mu$), the emissivity of the surface, and the chemical composition of the surface. These effects may be distinguishable to some extent in the spectra, and some information gained about each. If the emissivity can be determined, it will be helpful in analyzing the 8–12$\mu$ IRR data, allowing one to calculate the actual surface temperature rather than the effective black-body temperatures. |

Again, these quantities may vary with Martian geographic locale.

## D. Ultraviolet Spectrometer

The UVS data to be taken will start when the projected slit image is about 1000 km above the lighted limb of Mars. The image of the UVS slit in space at 100 km above the Martian limb will be parallel (within $\pm 3$ deg) along its length to the tangent to the Martian surface at the subimage point. At a slant range of 6000 km, the dimensions of the column of space viewed by the slit are $24 \times 240$ km. One complete spectral scan is made every 3 s, with 200 samples per second from each channel.

| *Key* | *Expected Results* |
|---|---|
| a | The atmospheric species that are the prime objectives of the UVS experiment are H(1216 Å), O(1304 Å), N(1200 Å), $N_2$(3914 Å), CO (4264 Å), $N_2$(1354, 3371 Å), NO(2150 Å), CO(2160 Å), and CN(3876 Å). The wavelengths listed are the optimum wavelengths where the species will be sought. While there may not be sufficient solar energy to excite other atmospheric species, it will be a secondary objective to seek other species, such as Kr(1235 Å), Xe(1470 Å), and metallic ions, and other molecules in the spectral range being examined. |
| b | The altitude range where these species will be sought and a nominal value for the scale height of each species (based on present knowledge of the Martian atmosphere) are as follows: |

| *Species* | *Range, km* | *Height, km* |
|---|---|---|
| H | 250–30,000 | 1000 |
| O | 250–1000 | 70 |
| N | 100–200 | 70 |
| $N_2$ | 250–400 | 70 |
| CO | 250–400 | 70 |
| $N_2$ | 100–200 | 24 |
| NO | 100–200 | 24 |
| CO | 100–200 | 24 |
| CN | 100–200 | 24 |

| | |
|---|---|
| c | Just prior to UVS limb crossing, the instrument will see Rayleigh scattered light from the lower atmosphere of Mars. At 4000 Å, reflected light from the planetary surface may be very nearly equal to the scattered component, but, at shorter wavelengths, the Rayleigh scattering will undoubtedly predominate. As the instrument crosses the limb of the planet, the longer wavelength (N) channel sensitivity will be reduced so that reflected sunlight from the planet will not saturate the instrument. The G channel is essentially solar-blind, thus needs no change in sensitivity. The Martian phase angle relative to the spacecraft will be known at all times during encounter. It will thus be possible to make a quantitative estimate of the number of Rayleigh scattering elements within the field-of-view of the slit. The contribution of reflected light to the measurements on the lighted side of the planet may also be determined by measuring Rayleigh scattering just past the terminator (with the slit aligned tangent to the terminator) where it is certain there is no reflected light from the surface. Comparison of the daylight-side spectra with the spectra at the terminator may allow the experimenters to make a quantitative estimate of the amount of UV radiation actually reaching the surface of Mars. As the lighted portion of the disk is being traversed, sudden drops in intensity may be experienced due to high-altitude UV-obscuring clouds, whose presence and extent may thus be inferred. It may also be possible to detect $O_3$ absorption in the 2400–2800-Å region of the spectrum. As measurements proceed further and further beyond the terminator, successively higher regions of the atmosphere will be measured (as the lower atmosphere becomes shadowed), thus giving a profile of particle density as a function of height. This measurement will act as a back up for the S-band occultation experiment. There exists also the possibility that night-glow might be detectable off the dark limb of the planet. |

## E. S-Band Occultation

| *Key* | *Expected Results* |
|---|---|
| a | In contrast to the *Mariner IV* data, two independent spacecraft will provide four separate Martian surface pressure measurements. This should help to explain the differences between the *Mariner IV* immersion and emersion data. Present estimates seem to indicate that the *Mariner IV* emersion data are more representative of the true surface pressure. Since the atmospheric composition will be better known through the results of the UVS and IRS investigations, the model used by the occultation experimenters to determine the surface pressure will be more accurate than that of *Mariner IV*. Similarly, the change |

in refractivity with altitude in the atmosphere will yield a somewhat more precise pressure profile when the composition is known. Also, inasmuch as the four occultation points will be widely separated in latitude, a rough estimate of the variation (if any) of surface pressure with latitude will be possible.

b During the *Mariner* Mars 1969 encounter, the solar activity will be near a maximum. The electron density in the Martian ionosphere should consequently be higher than that during the *Mariner IV* flyby. The density may reach a maximum of about $10^6$ electrons-cm$^{-3}$ and the altitude in the atmosphere where the maximum occurs may be somewhat lower than the 123 km obtained from *Mariner IV*. Scale heights will probably still be about 22 km, the value obtained from *Mariner IV*. *Mariner* Mars 1969 will be able to refine these values in addition to looking for variations with latitude. There will also be a check on the magnitude of the nighttime ionospheric electron density of Mars, which, according to the *Mariner IV* data, was at least a factor of 20 smaller than the daytime ionosphere.

c It is hoped that one of the two *Mariner* Mars 1969 spacecraft will make a near-diametrical pass behind Mars and that the other will have entrance and exit occultation points near the equator and one pole. The four measurements of the radius of Mars may possibly settle the question as to whether the flattening of Mars more nearly approximates the dynamic value (0.00525) or the optical value (0.0105 in yellow light). The former seems, at present, to be the more likely value. The *Mariner IV* exit occultation data, taken in conjunction with this flattening, yield an equatorial radius of 3393 $\pm$ 3 km and a polar radius of 3375 $\pm$ 3 km.

### F. Celestial Mechanics

The sole item of information about Mars that the celestial mechanics experiment will provide is the mass of Mars, which from *Mariner IV* was found to be 1/(3,098,000 $\pm$ 3,000) solar masses. It is possible that improved range data for *Mariner* Mars 1969 may reduce the error bars somewhat. It is extremely unlikely that either spacecraft will pass close enough to either of the satellites of Mars to yield even rough estimates of the satellite masses.

## III. Implications for Planetary Questions

The following comments are keyed to the questions given in Section IV of the Mars chapter.

### A. Planetology

(1) The celestial mechanics experiment will provide an improved value for the mass of Mars. Far-encounter TV (extended sequence), especially when coupled with S-band occultation measurements for control, should provide the shape (figure) of the planet to within a few km. Thus, the mean density can also be computed. The moments of inertia of Mars will not be improved by *Mariner* Mars 1969 data over the values determined from the orbits of Phobos and Deimos.

(2) The shape (figure) of Mars, subject to possible errors caused by the atmosphere, will be provided to within a few km (see above item 1).

(3) The IRR investigation will provide a more precise value for the thermal inertia of Mars than that presently available. The variation of thermal inertia between light and dark areas (if there is a difference) may also be apparent. High-resolution TV (camera B) at encounter can be a source of information on past seismic activity (through observed fault lines, distorted craters, etc.), but it probably will not conclusively show present seismic activity.

(4) The IRS experiment may provide some information on the surface composition of Mars for constituents with absorption between 1.9 and 6.0$\mu$.

(5) The TV pictures can indicate average slopes on scales of several km down to about 1 km at best. Far-encounter TV imaging could reveal large features (mountain ranges and large local depressions) near the terminator and possibly at the illuminated limb, if the scale involved is at least several km and providing that atmospheric effects do not interfere.

(6) If the approximate sizes of the satellites can be determined in far-encounter TV imaging, albedo estimates may be possible, which in turn could place some bounds on possible surface composition.

(7) Refer to item 3 under the following atmosphere heading.

## B. Atmosphere

(1) If present in detectable quantities, the atmospheric constituents mentioned in the UVS experiment description will be measured and scale height data derived for each. Similar data should be available for the atmospheric constituents measured by the IRS, though in the latter case the scale height data may be more heavily dependent upon atmospheric models.

(2) The IRS is equipped to detect the organic molecules of methane, ethylene, acetylene, and methanol, any of which may have biological origin.

(3) Provided the reflection spectra of ices subject to Martian conditions are sufficiently well known, the IRS may have sufficient resolution to determine polar cap composition. Temperature sensing by the IRR should be sufficient to differentiate between a "pure" water cap and one that is composed primarily of carbon dioxide ice.

(4) UVS measurements of Rayleigh scattering in the twilight atmosphere of Mars will be made by both spacecraft. Four other measurements of the atmospheric density profile will be provided by the S-band occultation experiment. Models of the temperature–pressure profile of the Mars atmosphere, constructed from these data, must also be consistent with water and carbon dioxide band profiles measured by the IRS.

(5) Far-encounter TV (extended sequence) may provide some information on cloud formation and motion. Near-encounter wide-angle TV imagery will provide stereoscopic viewing of overlap areas; thus, if clouds or hazes are present in these areas, a rough estimate of their altitudes can be made.

(6) In addition to circulation data obtained from the cloud and haze data mentioned in above item 5, prevailing wind directions may be indicated by sand dunes or other such wind-dependent linear structures, if they are present at a sufficiently large scale to be seen in TV pictures.

## C. Biology

(1) Landed life-detection experiments are outside the scope of *Mariner* Mars 1969.

(2) Landed soil organic analysis experiments are outside the scope of *Mariner* Mars 1969.

(3) The combination of TV imagery and IRR temperature sensing by *Mariner* Mars 1969 may indicate areas of possible interest for future landing site studies. Failing this indication, the data may be well enough correlated with terrain and latitude to indicate where suitable landing sites might be sought on the planet.

(4) The IRS experiment may provide information about the amount of water vapor at various locations on the planet. At Martian pressures and temperatures, it is unlikely that liquid water would ever be present in large enough quantities or great enough surface extent to be detected by any of the *Mariner* Mars 1969 experiments.

(5) If concentrations of atmospheric trace constituents exceed 0.0002% of the total atmosphere within the field-of-view of the IRS, they might be detectable (provided, of course, they have absorption bands in the 1.9–14.3$\mu$ spectral region that are as strong as, for example, the methane absorption).

(6) *Mariner* Mars 1969 is not adapted to the measurement of diurnal atmospheric variation, except, perhaps, as might be indicated by IRS measurements at different distances from the subsolar point.

(7) The UVS has the capability of measuring the atmospheric constituents mentioned in Section II-D-a of this appendix, but only at four places: in the atmosphere above the lighted limb and near the terminator (for each of the two spacecraft).

(8) Landed experiments (including surface mineralogy) are outside the capabilities of *Mariner* Mars 1969.

## D. Wave of Darkening

*Mariner* Mars 1969 spacecraft arrival time will not be optimum for observing the wave of darkening. The spacecraft will arrive early in the southern spring, just as the darkening is starting.

## Appendix B

## Importance of the Clouds of Venus and Their *In Situ* Study

One of the questions about Venus that seems most urgent to answer relates to the nature of the clouds. Knowledge of their composition may have far-reaching implications for surface or atmospheric composition and possibly for atmospheric dynamics. Ground-based polarization data have already shown that the cloud particles are dielectric, with relatively small absorption. Because of the effects of multiple scattering and a distribution of particle sizes, it is doubtful that a very accurate value will be found for the (complex) refractive index of the particles. Even if the refractive index were known exactly, it would still be difficult to identify the cloud particle material, since many different substances have similar refractive indices, and the absorption could be due to various impurities.

One puzzling feature of the clouds is that they appear to have an "anti-greenhouse-effect" on heating of the atmosphere. That is, they seem to prevent the incident solar radiation from reaching the surface of Venus, and the cloud-tops radiate in the infrared. The amount of solar radiation that penetrates the clouds depends on the thickness of the cloud layer, the size distribution of the particles, and the single scattering albedo. Unfortunately, the thickness and optical properties of the lower layers of the clouds are completely inaccessible to observation from above the clouds, unless occasionally localized clearings occur.

The optical properties of the clouds need to be known in detail, both for the interpretation of optical and infrared spectra, and for the determination of whether the high surface temperature is due to the greenhouse effect of atmospheric gases. These problems are unlikely to be solved by observations made from outside the Venus atmosphere.

# Appendix C

## Importance of Inert Atmospheric Components and Their Isotopic Analysis

*F. Fanale*

Complete atmospheric chemical and isotopic analysis of the Cytherean atmosphere is prerequisite to understanding its origin and evolution. Such an understanding could, in turn, shed much light on the origin and history of the planet itself. In addition, it would aid in evaluation of the present and past suitability of the Cytherean environment for origination and support of primitive life – both on the surface and in the atmosphere. Finally, such a knowledge (of composition) can be considered, along with pressure profiles, as essential for the satisfactory planning of potentially more elaborate and sophisticated future missions.

The most likely contributing sources of the Cytherean atmosphere include:

(1) Continual or early, episodic outgassing of the interior (associated with bulk planetary differentiation and/or crustal formation).

(2) Outgassing of "planetesimals" during accretion.

(3) An initially present, or slowly accreted, solar or solar wind component.

In addition, the Cytherean atmosphere may have been significantly modified by photodissociation and thermal escape of light constituents, and by high-temperature equilibration of the chemically reactive constituents with each other and with solid mineral phases comprising the surface and near-surface rocks.

Unfortunately, most diagnostic data (those which most distinguish between the various likely contributing sources of the Cytherean atmosphere, and best reveal their relative importance) involve elemental and isotopic analysis of the "inert" component; i.e., $N_2$ and the rare gases. We lack these data, and they are difficult or impossible to obtain by spectroscopic means alone. Data from a wide-range mass-scanning device (presumably a mass spectrometer) on an entry probe or a balloon would, therefore, seem to be essential for obtaining an understanding of Cytherean atmospheric origin, together with its planetological implications.

For example, the abundance of the nuclides $Ne^{20}$, $Ne^{22}$, $Ar^{36}$, and $Ar^{38}$ would reveal the importance of the solar or primordial component. Other rare gas nuclides, such as radiogenic $Ar^{40}$, originate by decay of unstable parent nuclides in the interior of the planet throughout its history. An absolute abundance of radiogenic $Ar^{40}$ comparable with the terrestrial abundance would almost certainly indicate extensive planetary differentiation.

If the ratio of the total "inert gas" content to that of $CO_2$ were found to be higher than the ratio of terrestrial atmospheric $N_2$ to the $CO_2$ represented by the terrestrial carbonate inventory, some chemical removal by reaction with the surface would be indicated. Cold-trapping appears to be ruled out by present-surface conditions, while present exospheric escape of intermediate mass species (say $M \geq 16$) also appears impossible. The *initial* composition of volatiles occluded and chemically combined in dust at the Cytherean position of the primordial cloud may have been different from that of the Earth – much as Mercury's Fe/Si ratio appears to have been greatly augmented by early, intense dispersed-state heating prior to accretion. However, a careful study of the elemental and isotopic composition of the inert component will allow this variable to be evaluated. This is an important point – bearing, as it does, on the possibly initially anhydrous condition of the accreting Cytherean particles. Theoretical estimates indicate that it is unlikely that much "replacement" (sweeping + accretion) by solar wind has taken place in the (massive) Cytherean atmosphere. But it is not known how much more intense the solar wind may have been at earlier stages of solar evolution, just as information is not available on *past* exospheric temperatures. Abundances and isotopic analyses of the inert components should provide definite answers on these points.

The above sets of hypothesized observations and interpretations are offered only as illustrations of the wide range of valuable planetological and other types of information that can be gleaned from total atmospheric analysis.

# Appendix D

# Determination of Water Vapor in the Cytherean Atmosphere

C. B. Farmer

## I. Atmosphere In and Above the Clouds

At visible and near-infrared wavelengths, the cloud-top layer appears to be in the range 40–300 mbar (to cite extreme values of different investigations) and to be at a temperature between 235 and 250°K. If the atmosphere were saturated at the cloud tops and a constant mixing ratio for water vapor existed above this level (extremely improbable), the upper-limit water content would be 1 part in $10^7$. Although this limit implies a large total water content above the clouds (> 1 mm), it would be difficult to detect such water by means other than molecular spectroscopy. However, if this amount were present, it would very easily have been detected in the observations that have been made; i.e., in the 8600 Å, 1.8$\mu$ and 2.7$\mu$ regions.

Such positive detections of water vapor as have been claimed give estimated contents varying from zero to ~ 100$\mu$, and are in most cases detected by doppler-shifted lines in the presence of very much larger absorption by water in the Earth's atmosphere. The considerable differences in the estimated amounts may well be the result of real variations in the Venus atmosphere in and above the clouds. Taking all of these factors into account, the most satisfactory method of determining the amount of water vapor above the clouds, and its variation with altitude, would be by high-resolution spectroscopy at a suitable wavelength from an orbiter, with some of the spectra being obtained from solar occultation measurements.

## II. The Atmosphere Below the Clouds

For the lower atmosphere, the problem is, in many ways, quite different. From arguments based on application to the visible phase curve of a more refined scattering theory than has been used in the past, and from the dynamics of a hot dense atmosphere (such as that of Venus), it seems very probable that the cloud particles have a size distribution whose mode radius is of the order 1/2–1$\mu$.

Although small by volume occupancy, the nitrogen present in the Venus atmosphere will, at the comparatively high pressures involved below 20-km altitude, produce very strong absorption by the collision-induced fundamental vibration band at wavelengths between 3.9 and 5$\mu$ (and, of course, a rotational band at longer wavelengths). One would expect, therefore, not to observe any significant change of apparent atmospheric temperature at wavelengths shorter than about 4$\mu$, and to see a decrease in albedo accompanied by increasing temperature at longer wavelengths. A rapid change in albedo at 3.0$\mu$ was observed by Kuiper and by Moroz.

In the lower atmosphere, the water vapor, if present, would be expected to increase in mass mixing ratio as altitude decreases; but, if this increase does not occur, the percent water content may still be too low to be detected using direct methods; i.e., by capacitative probes or mass spectroscopy. (To take a worst case, the Russian *Venus 4* result may represent a local maximum concentration resulting from near saturation in the condensation region.)

It would appear then that the method most likely to succeed in the detection and measurement of the water vapor below the cloud layer would be infrared spectroscopy at wavelengths that would penetrate both the $CO_2$ and the cloud layer(s); the strong central part of the rotational band between 30 and 100$\mu$ should be ideal for this purpose. A spectral resolution of about 0.5 cm$^{-1}$ would allow the line structure to be observed when absorption occurs at pressure altitudes of 1–2 atm, and a spectral coverage of from 10 to 100$\mu$ would allow meaningful interpretations to be made for a very large range of possible water contents.

Again, two modes of operation are desirable: direct absorption/emission spectroscopy of a portion of the planetary disk presented to an orbiting instrument, coupled with solar occultation measurements. The required resolution and wavelength range (i.e., approximately 2000 spectral elements) indicates the use of a small interferometric spectrometer with a fast thermal detector as the optimum choice of instrumentation.

# Appendix E

## Effective Temperature of Jupiter

The brightness temperature $T_b$ of a body is the temperature that a black body would have to assume in order to give the same energy output per unit wavelength at a given wavelength as that actually observed. The effective temperature $T_e$ of a spherical body is defined by:

$$L = 4\pi R^2 \sigma T_e^4$$

where $L$ is the luminosity (total energy output) of the body, $R$ is its radius, and $\sigma$ is the Stefan-Boltzmann constant. The effective temperature then is an averaged brightness temperature, the temperature that a black body would have to assume in order to emit the same total energy as the real body in question. In studies of planetary energy balance, the effective temperature is the significant quantity. Unfortunately, many wavelengths are inaccessible through the Earth's atmosphere; thus all measurements of planetary temperature are necessarily brightness temperatures over some finite wavelength range.

Recent measurements of Jupiter's brightness temperature are listed in Table E-1 (references cited in the table can be found by using the general references listed at the end of the Jupiter chapter). Brightness measurements at longer wavelengths have a nonthermal component originating in the Jovian radiation belts (see Section C). The last two entries in the table reflect attempts to separate thermal from nonthermal components. These results may be indicative of the higher temperatures that almost certainly exist beneath the clouds.

Brightness temperatures have also been measured in the 1.1–1.6-cm range by Staelin and Neal. The results at five different wavelengths vary from 98 to 123°K, and must refer specifically to a rotational line of ammonia centered at 1.28 cm. Other temperatures are often quoted for the cloud tops, stratosphere, etc., but these are the result of conclusions about the atmosphere of Jupiter, rather than measurements and are, therefore, discussed in Section II-A-4 of the Jupiter chapter, on atmospheric structure.

**Table E-1. Recent measurements of Jupiter's brightness temperature**

| Wavelength | $T_b$, °K | Reference | Date |
|---|---|---|---|
| **Thermal components only** | | | |
| 8–14$\mu$ | 128 ± 2.3[a] | Murray and Wildey | 1963 |
| 8–14$\mu$ | 128.5 ± 2.0[a] | Murray, Wildey, and Westphal | 1964 |
| 8.8$\mu$ | 139 | Sinton | 1964 |
| 17.5–25$\mu$ | 150 ± 5 (equator)<br>130 (poles) | Low | 1966 |
| 1 mm | 155 ± 15 | Low and Davidson | 1965 |
| 3.19 mm | 111 $^{+22}_{-11}$ | Tolbert | 1966 |
| 4.29 mm | 105 $^{+18}_{-12}$ | Tolbert | 1966 |
| 8.35 mm | 144 ± 23 | Thornton and Welch | 1963 |
| 8.57 mm | 113 ± 11 | Tolbert | 1966 |
| 8.6 mm | 140 $^{+18}_{-14}$ | Kalaghan and Wulfsberg | 1967 |
| **With nonthermal components** | | | |
| 6 cm | 224 | Dickel | 1967 |
| 10.4 cm | 260 | Berge | 1966 |

[a]At the subsolar point.

# Appendix F

## Photometric Properties of Jupiter

Photometric properties of an entire planet include magnitude (brightness) and color as a function of phase, geometric albedo, and Bond albedo. These may all vary somewhat with time as a planet rotates or if it has an active atmosphere, which Jupiter certainly does. With sufficient geometric resolution, limb darkening curves and point-by-point study of a planetary disk can be made. Each of these properties is important scientifically, both in attempts to understand a planet and in an engineering sense for proper design of imaging systems, radiometers, etc.

The Bond albedo (or Russell-Bond albedo) is that fraction of the total parallel incident flux reflected in all directions by a body. It can be decomposed into two parts: the geometric albedo, which is that fraction of the total parallel incident flux reflected back in the direction from which it came; and the phase integral, a multiplier that averages the variation in reflection with phase angle. This decomposition is an important distinction for the major planets, because the geometric albedo can be directly measured from Earth while the phase integral can not, since none of the major planets ever exceeds a phase angle of 12 deg as seen from Earth. Albedo is a function of wavelength, particularly large variations being caused by extensive molecular absorption bands in some regions of the spectrum.

Energy balance studies obviously require the value of the Bond albedo integrated over all wavelengths; that is, the *bolometric* Bond albedo. Taylor has measured a bolometric geometric albedo and has assumed a bolometric phase integral of 1.6 to derive a bolometric Bond albedo of 0.45. He considers the uncertainty in his value to be about ±15%.